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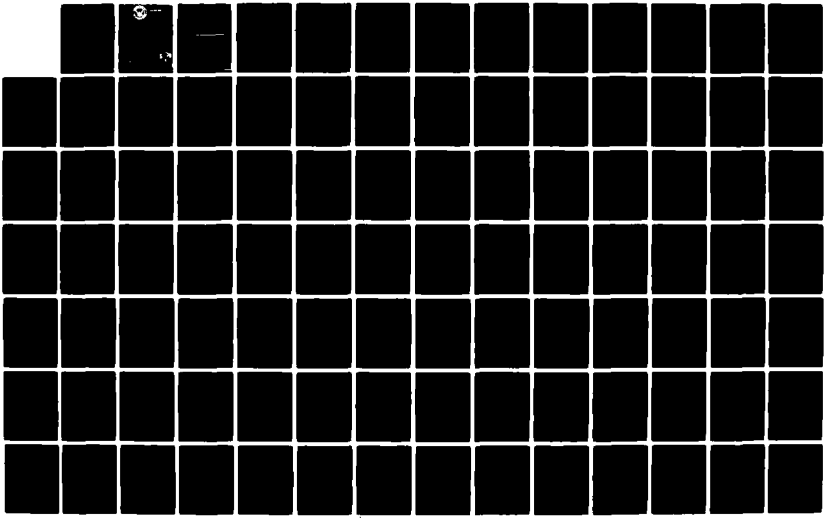

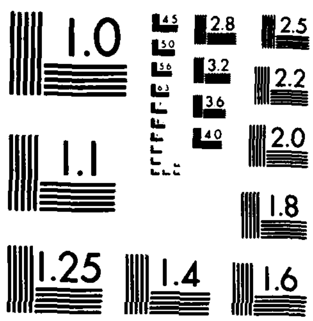

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AIR LEAKAGE MEASUREMENTS IN NAVY FAMILY HOUSING UNITS AT NORFOLK, VIRGINIA

April 1983

An Investigation Conducted by
S-CUBED
P. O. Box 1620
La Jolla, California

N68305-79-C-00344

METRIC CONVERSION FACTORS

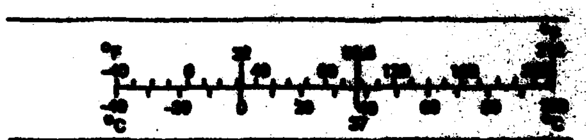
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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A series of tests were conducted in 24 Navy family housing units to determine the effectiveness of three retrofit techniques in reducing air leakage. Effectiveness was determined by fan pressurization/depressurization tests before and after the retrofits were installed. In two other housing units, other types of retrofits were simulated by using tape and plastic

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sheeting at suspected leakage points.

This report covers the measurement techniques used, air leakage data collected, and conclusions and recommendations based on the tests.

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1. INTRODUCTION AND SUMMARY

Air leakage measurements were performed in twenty-six, separate, three-bedroom apartment units in the Willoughby Bay area of the Norfolk Navy base during the periods from 11/27/79 to 12/4/79, from 10/15/80 to 10/22/80, and from 7/20/81 to 7/24/81, 1981. Twenty-four of these units were contained in four sixplexes -- differentiated only by the possession of different retrofit measures aimed at reducing air leakage within these structures. The twenty-fifth and twenty-sixth units were unoccupied apartments in additional sixplexes. These apartments were used to make detailed air leakage measurements in which various potential leak-sealing retrofits were approximated by using tape and builders plastic sheeting to provide seals at suspected leakage points.

The underlying objective of the measurement program was to determine the effectiveness of three specific building retrofit techniques in reducing air leakage in the structures. Air leakage rates were measured primarily by using the fan pressurization method. A smaller amount of air leakage data was obtained utilizing sulfur hexafluoride tracer gas concentration decay to infer an air leakage rate under ambient conditions. Local meteorological data were obtained for the Willoughby Bay area during all measurement periods.

In Section 2 of this report, we provide background information necessary to the understanding of the measurement techniques utilized in this study; in Section 3 we provide the experimental data and techniques utilized during the measurement periods; in Section 4 we provide a discussion of the various data presented in Section 3; in Section 5 we provide conclusions and recommendations based on the study. Also included in this report are three appendices: in Appendix A we provide induced flow versus pressure curves for all of the apartments measured in the study; in Appendix B we provide tracer concentration decay data for the various units in which measurements were undertaken; in Appendix C we provide a simple numerical simulation of the measured energy consumption within one apartment unit in the Willoughby Bay complex -- the purpose of this Appendix is to demonstrate the utility of a widely-available code (NBSLD), coupled with actual air leakage data inferred from previous measurement programs.

2. BACKGROUND

Air leakage (infiltration) represents an important part of the heating and cooling load of residential, commercial, and industrial buildings. It is also an important parameter in indoor-outdoor air pollution relationships. The heat loss associated with air leakage through the enclosure of a typical house may be as much as 40 percent of the total heat load [1].

Considerable energy savings can be realized by reducing the air leakage in a structure. A numerical simulation [2] of the heating requirements for a two-story residence (conforming to a minimum FHA standard) demonstrated that a 24 percent energy savings could be realized by reducing the air leakage 50 percent (i.e., from one to one-half air changes per hour).

Air leakage (infiltration) is difficult to quantify because it is not only a function of building tightness and configuration, but also of inside-outside temperature differences, wind speed and direction, and possibly other factors. Standard formulae exist to estimate air-exchange rates [3], but they are at best rough approximations, since actual leakage rates often depend on non-calculable quantities such as the quality of workmanship in construction.

There are two major methods of quantifying the air leakage rate or air tightness of a structure -- namely, the tracer dilution method and the induced pressure techniques. The tracer dilution method is a direct way of measuring the air leakage rate of a structure under the variables of ambient wind and temperature. The induced pressure technique is an indirect method; i.e., it measures the total air flow. This parameter, however, can be related to the air leakage rate under the same pressure.

One way to test a building for air leakage is to use a fan either to pump air into the building or out of it, while measuring both the flow and the resulting inside-to-outside pressure difference [1, 4-7]. All interior doors would be open, and all windows and exterior doors would be closed.

In general, air leakage would take place through numerous passages around window sashes, doors, and elsewhere. The geometry of each of these passages would, in general, be quite complicated -- yielding a complicated flow-versus-pressure difference characteristic. Thus, the total flow through all of the passages will also be complicated so that a simple and accurate theoretically-derived expression for the total flow-versus-pressure difference characteristic of a building does not exist.

In view of the difficulties with employing a purely theoretical approach, most work on the air leakage properties of buildings employs an empirical approach. Laboratory measurements show that an equation of the form

$$Q = K (\Delta P)^n \tag{1}$$

characterizes the flow-versus-pressure difference behavior in most cases. Here K and n are experimental constants, with n usually in the range 1/2 to 2/3.

Normally, induced pressure is plotted against flow for a given structure. Changes in the flow due to retrofitting are readily apparent in this technique, thus making it an ideal method for investigating the effects of various retrofits on air leakage. Note that this technique is embodied in ASTM Standard Practice E774-81 (Measuring Air Leakage by the Fan Pressurization Method).

The tracer dilution method has been used for a number of years to measure air leakage rates under ambient conditions [8-16]. The technique entails introducing a small amount of tracer gas into a structure and measuring the rate of change (decay) in tracer concentration. The air change rate (generally air changes per hour, abbreviated ACPH) can be determined from the logarithmic decay rate of tracer concentration with respect to time.

The principle of the tracer dilution method of easuring air exchange rates may be developed briefly by considering the rage rate L at which air leaks into a structure. This must equal the rage rate at which air leaks out, unless there is a steady increase ecrease in pressure. The rate of change in the total amount of tracer in the structure is:

$$\frac{dQ}{dt} = (C_{out} - C_{in}) L \quad , \tag{2}$$

where Q is the total amount of tracer, and C_{out} and C_{in} are the concentrations of tracer outside and inside. If V is the total internal volume of the structure, Equation (1) may be expressed:

$$\frac{1}{V}\frac{dQ}{dt} = \frac{dC_{in}}{dt} = (C_{out} - C_{in}) \frac{L}{V} \quad , \tag{3}$$

where L/V is the air leakage (infiltration) rate in air changes per unit time. If the outside concentration of tracer is small enough to be neglected, Equation (2) reduces to:

$$\frac{dC}{dt} = -C \frac{L}{V} \quad , \tag{4}$$

where we have suppressed the subscripts, and tacitly assumed that C always refers to the inside concentration.

Integrating Equation (3) leads to:

$$C = C_o e^{-(L/V)t} \quad , \tag{5}$$

where C_o is the concentration at time (t) = 0.

Equation (4) may be re-written to give

$$I = \frac{L}{V} = \frac{1}{t} \ln \left(\frac{C_o}{C}\right) \quad . \tag{6}$$

This equation is the theoretical basis of tracer studies of room and building air exchange.

Stated another way, we have shown that the air change rate in an enclosed space during a selected time interval is directly proportional to the natural logarithm of the ratio of the concentrations of the tracer gas at the beginning and end of the time interval, assuming that the factors causing air leakage (infiltration) remain constant. A constant air change rate is then represented by a straight line of semi-logarithmic paper.

We should note that this technique is embodied in ASTM Standard Practice E741-80 ("Measuring Air Leakage Rate by the Tracer Dilution Method").

3. MEASUREMENTS AND DISCUSSION

The relative location of the apartments within the four sixplexes chosen for measurement is shown on Figure 1. Living units are identified by street addresses on O'Connor Crescent. Building 114 was chosen to be the control for this series of tests, and no retrofit measures were imposed on it. Apartment numbers in the structure run from 8160 to 8165.

Building 112 was retrofitted with commercially-available, polystyrene, one-inch-thick tongue-and-groove insulation boards installed on all exterior walls except for areas covered with brick veneer. New aluminum siding was installed over the polystyrene insulation. Apartment numbers in this structure ran from 8148 to 8153.

Building 108 was retrofitted with a commercially-available fiberglass and mastic wall covering system. This was applied to the interior surfaces of all exterior walls. The following steps were used in installing this covering:

- Baseboards, door and window trim, and outlet and light switch covers were removed. Any carpeting was pulled away from the tack strip.
- A white plastic adhesive was applied to all surfaces to be covered with a paint roller and brush.
- The fiberglass sheeting was applied over, and worked into, the wet adhesive. The sheeting was extended unto the floor about one-half inch to seal the floor-sillplate joint. All sheets were overlapped by one inch for positive sealing.
- Baseboards and trim were re-installed, the walls were repainted, and the switch and recepticle plates were re-installed.
- A second coat of adhesive was applied when the fiberglass sheeting was set by the first coat.

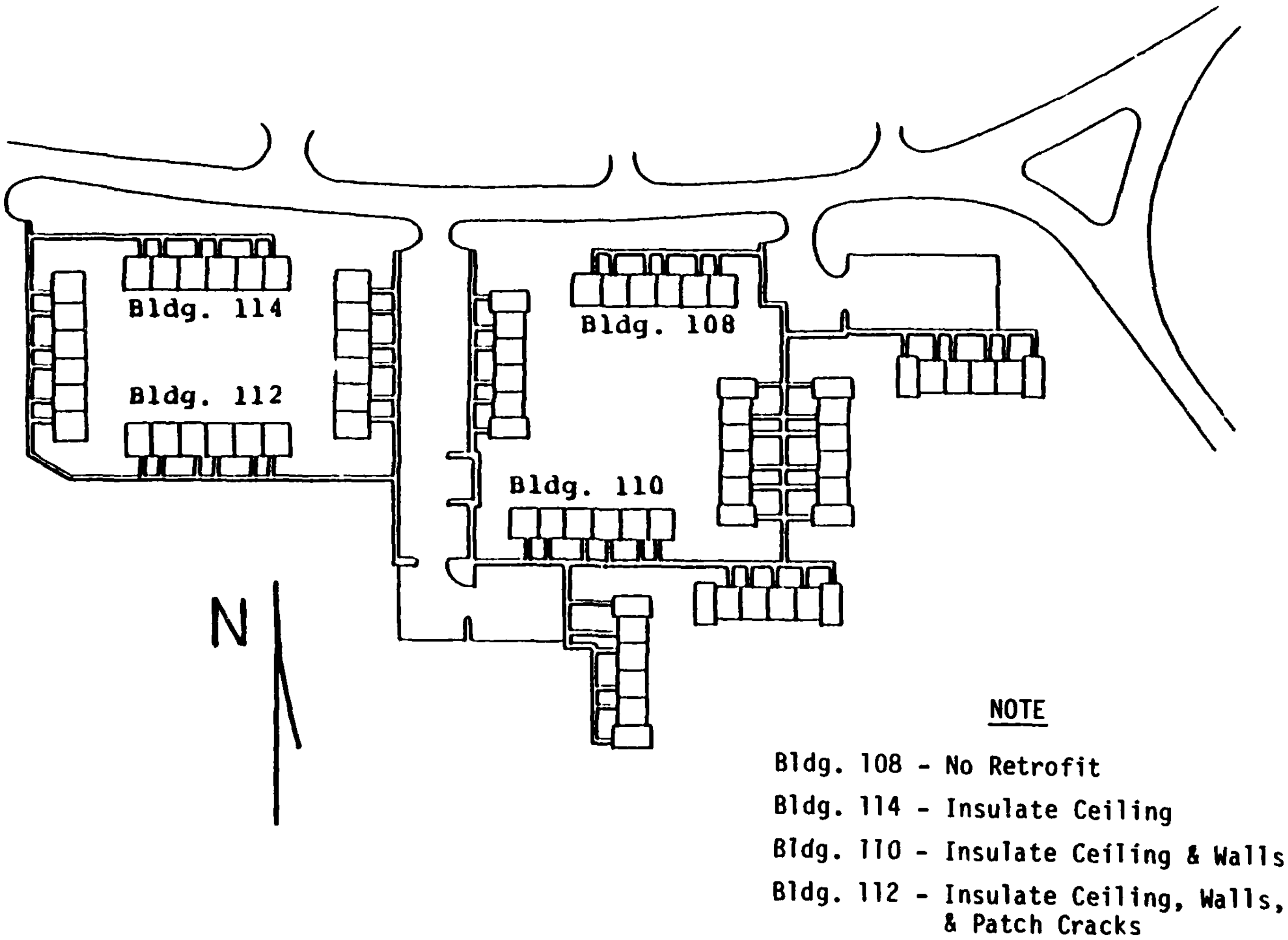

Figure 1. Willoughby Bay Housing Units.

When completed, it was difficult to distinguish between the retrofitted and conventional walls except for a slight texture or "fuzziness" on the retrofitted surfaces. Public Works tradesmen who had not installed this type of wall system before did not encounter difficulties, and indicated it was about like installing conventional wallpaper. Apartment numbers in this sixplex run from 8118 to 8123.

Building 110 was retrofitted with the same mastic, fiberglass, and procedures as Building 108, except that 3 to 4-inch-wide strips of fiberglass were used instead of sheets, and only cracks and joints behind baseboards and trim were covered instead of complete wall surfaces. Apartment numbers in this unit run from 8130 to 8135.

It should be emphasized that in the twenty-four apartment units tested, no attempt was made to block other sources of leakage. The apartments were occupied during the tests. Residents were requested to minimize ingress and egress, but data were taken on an "as available" basis.

In addition, detailed pressurization testing was performed in three units. Two of these units (8222 and 8709 O'Connor Crescent) were not contained within this four sixplex complex. However, they were unoccupied during the testing periods and consequently were available for detailed pressurization testing.

A final test was done in July 1981, in which Unit 8121 (within Building 108) became vacant. This apartment was made available to us for the express purpose of investigating the detailed pressurization characteristics of the various leakage apertures within the apartment, as well as allowing Navy personnel to perform a detailed inspection of the installation of the wall-covering system.

Individual apartment units were nominally identical, two-story, three-bedroom apartments, having roughly 1000 square feet of living space. A typical floor plan is shown on Figure 2. Gas-fired forced air

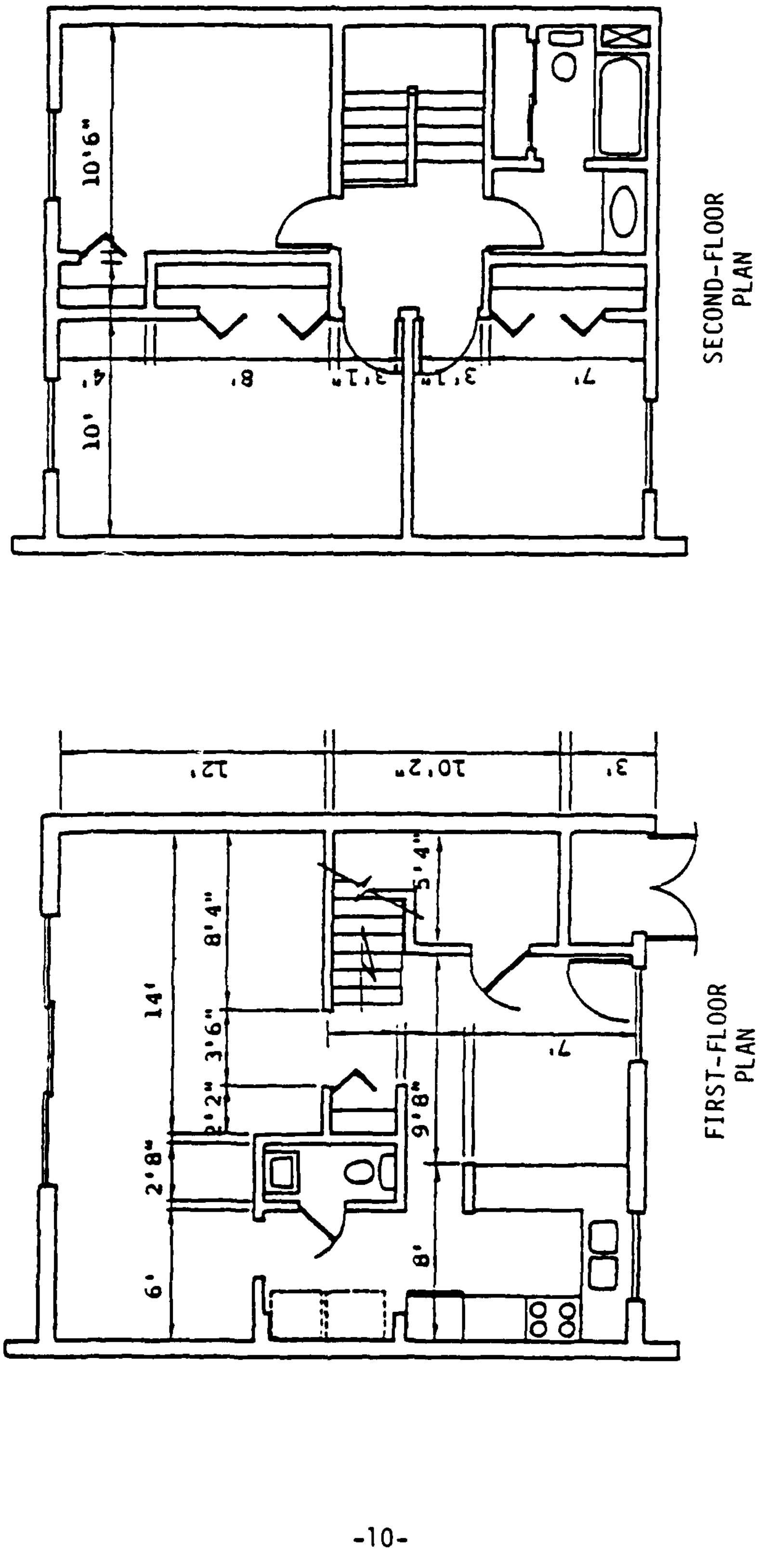

Figure 2. Floor Plan of Typical Three-Bedroom Apartments Measured During this Study.

provides heating, and electric air conditioning provides cooling. Heating and cooling are accomplished through a common ducting system. The gas-fired heater, as well as the HVAC blower, are accessible from an external utility room.

During the Fall of 1979, pressurization and evacuation testing was done in each of the apartments contained within Buildings 108, 110, 112, and 114. This testing was performed to obtain baseline flow data prior to applying the various retrofits described above.

BLOWER DOOR

Pressurization/evacuation testing was effected using a blower door borrowed from the U.S. Department of Energy. Before discussing the testing, we will describe this pressurization system in detail.

The blower door is a portable device used to exaggerate air leaks in a building envelope. It is basically a high-flow fan mounted on a plywood sheet, which is temporarily installed in an exterior door of a house. The house can then be either pressurized or evacuated, providing steady air leakage through cracks and openings. Leaks that may be obscure under natural infiltration conditions become obvious. In particular, leaks where air normally leaves the house, and cannot be felt by the resident, are easily detected by slightly evacuating the house so that all leaks flow inwards. A leakage profile (i.e., a plot of flowrate versus the inside-outside pressure difference induced by the blower), combined with blower calibration curves, provides a measure of the absolute leakiness of the house, independent of weather conditions. This capability enables the development of air leakage standards in building codes, such as the Swedish standard of air tightness in new houses. Exaggerating the leaks also allows one to determine the relative magnitudes of leaks, which often do not correspond to visual observations. If an air leakage reduction retrofit is done while the house is being pressurized or evacuated, an immediate check on the effectiveness of the retrofit measure can be obtained. In addition, it can be used as a quality control procedure for retrofits performed earlier.

Construction Details

The four major components of the blower door are the lower door assembly, the upper door assembly, the center plate assembly, and the instrument control panel. These are shown on Figure 3. It is designed to fit door openings 32 to 37 inches wide and 77 to 83 inches high.

The lower door assembly contains an 18-inch diameter spray booth fan, coupled by a low-friction, non-slipping, timing-belt drive system to an electrically-reversible, variable-speed, constant-torque DC motor. * The fan and motor assembly is mounted on a 3/4-inch plywood panel. Attached to one side of the plywood panel with jackscrews is a 1/16-inch aluminum slider panel. The jackscrews permit this panel to be moved sideways, in order to fit various door widths. There are also metal skids mounted on the lower door assembly, which serve to protect the control cable box and to facilitate loading.

The upper door assembly is similar to the lower door assembly, but without the fan and associated equipment. Its width is adjustable by another aluminum panel. The outside pressure tap is located in this assembly.

The aluminum cover plate assembly provides the height adjustment by forming a width-adjustable, height-adjustable bridge between the upper and lower door assemblies. This plate is held in place by three, spin-tight knobs and clamps.

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* A magnetic transducer-interrupter system (installed on the motor) is calibrated to read the fan rpm's.

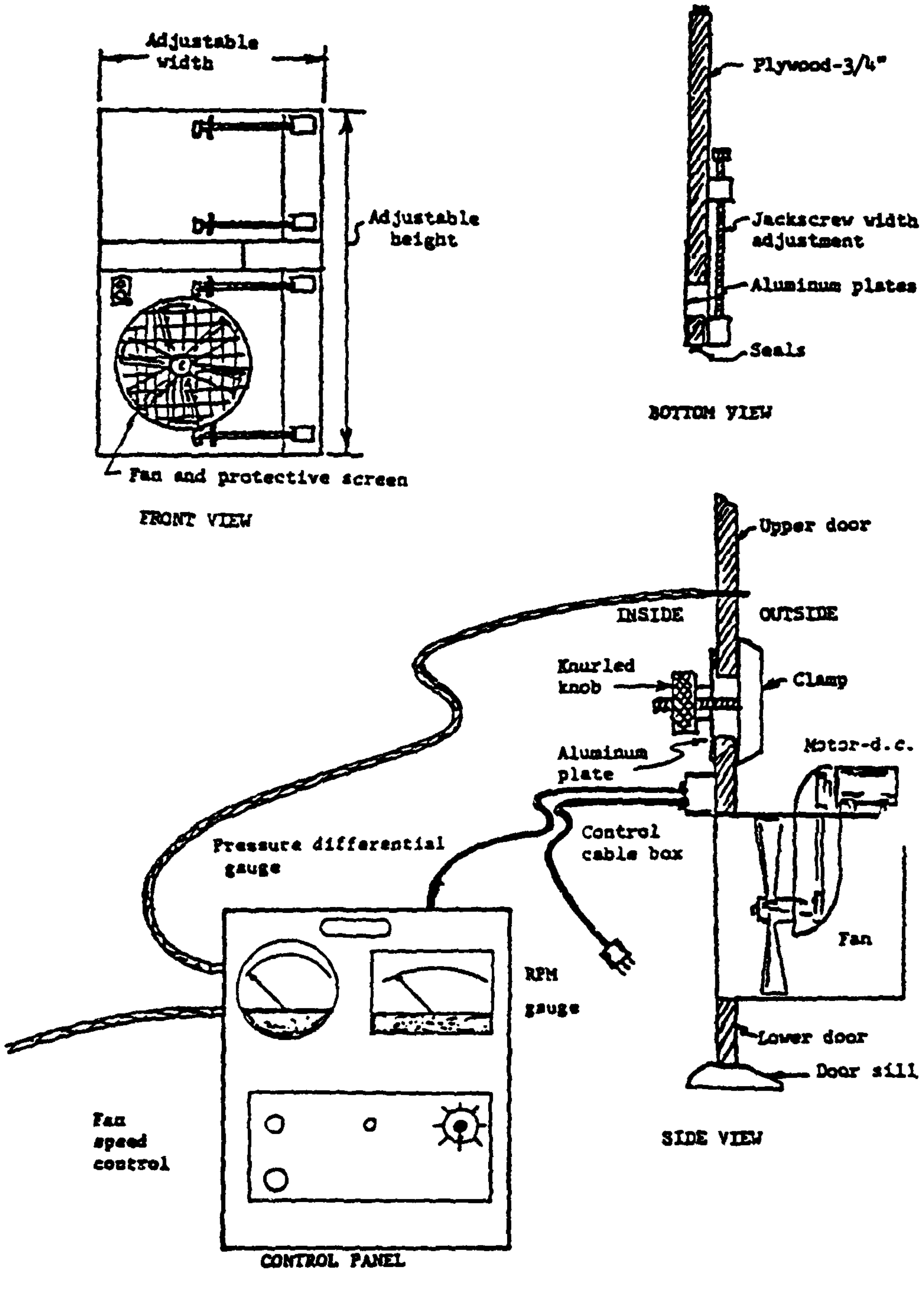

Figure 3. Blower Door Used in Family Housing Tests.

The instrument control panel contains the fan direction and speed control, the Magnehelic pressure gauge (0 to 0.5 inch of water full-scale, with a resolution of 0.01 inch of water) to measure the inside-outside pressure difference, and a tachometer circuit with either an analog or digital readout. A "bulls-eye" level is also installed on the panel to level the control panel and permit accurate pressure readings. Two, 10-foot lengths of flexible plastic tubing connect the pressure gauge to the inside and outside pressure taps. Also attached to the panel are an 8-foot, 115 VAC power cable, a 10-foot tachometer cable, and a 10-foot motor control cable.

The vertical edges of the upper and lower door assemblies are weather-stripped to reduce air leakage. A guard mounted along the bottom edge of the lower door assembly prevents chipping during installation and transportation.

Protective screens are mounted on both the inlet and outlet sides of the fan for safety. A guard is mounted over the motor pulley, both for safety and to protect the magnetic transducer assembly from accidental damage.

A typical experiment would consist of first pressurizing each apartment in 0.05-inch H_2O pressure steps and recording the corresponding flow at each of these induced pressures, up to a maximum pressure of 0.3-inch H_2O "positive."

The pressurization test would then be followed immediately by an evacuation test in which "negative" pressures from 0.05-inch H_2O to 0.3-inch H_2O would be obtained in 0.05-inch H_2O increments. The corresponding flows required to produce each of these negative pressures would then be recorded.

In addition, detailed pressurization measurements were performed in Apartment No.'s 8709 and 8222. These two units were similar to the twenty-four apartments being studied, and were unoccupied during the time of testing. Because of this, it was possible to investigate the relative reduction of induced air flow due to various retrofitting measures.

Within these two apartments, an attempt was made to seal obvious sources of air leakage by means of taping alone, or taping in conjunction with sheets of heavy builders plastic. By sequentially removing the tape and/or plastic coverings, one can measure the effects of individual component leakage on the entire leakage extant within a structure.

After the generation of the data from the Fall 1979 season, it became apparent that cross-apartment leakage had to be separated from the total leakage induced in each of the apartments. Accordingly, NCEL obtained three blower doors from GADZO, INC. for the Fall 1980 measurement season. These blowers were similar in construction and calibration to the blower door used in the 1979 measurement period. In operation, the apartment units on either side of an apartment of interest were pressurized to the same pressure at which flow measurements were being made in the apartment of interest. In this way, inter-apartment pressure differences were eliminated, thereby minimizing (or eliminating) cross-apartment leakage.

The detailed flow curves obtained for 1979 and 1980 are presented in Appendix A. In Table I we provide a summary of the flow at 0.2-inch H_2O positive differential pressure. Although flow data were obtained at many pressures, this pressure was chosen for data comparison as it is a common pressure at which structures in various parts of the United States (and, indeed, various parts of the world) are compared. In fact, the Swedish building standard requires a limit on the number of air exchanges (induced flowrate divided by volume) at this pressure. The corresponding number of air exchanges at 0.2-inch H_2O is given in the column denoted N. For comparison, the new Swedish building code requires N = 3.0. Accordingly, in Table I we provide the flow data obtained in 1979 for each of the apartments in question.

In Table II, the flow for 1980 is provided both in terms of single-blower measurements and also double or triple-blower measurements, in which the additional blowers have been used to minimize or eliminate cross-apartment leakage. Also provided in this table is the percent change between the single-blower flow measurement and the double or triple-blower flow measurement. This decrease in flow is that part of the flow into the apartment which is directly attributable to cross-apartment leakage, and not to leakage from the apartment to the outside.

In Tables III and IV we also provide detailed pressurization data (at 0.2-inch H_2O), in which various retrofits were attempted in order to allow measurement of the contribution of various leakage sources to the total leakage extant within an apartment. This testing is useful to illustrate the magnitude of leakage reduction which may be obtained by a given retrofit. It also provides an estimate of the total possible leakage reduction attainable by simple retrofitting.

Comparison of the blower door data obtained in 1979 and 1980, makes it apparent that within the precision of the data no systematic effect due to retrofit on the measured air leakage within the structure could be detected. Accordingly, it was decided to complete the investigation by waiting until one of the apartment units within the four sixplexes became vacant. Detailed pressurization testing would be performed within this apartment prior to re-occupancy. Accordingly, in July of 1981, detailed low flow range measurements were performed within Unit 8121, contained within Building 108. All wall, floor, and ceiling penetrations were measured. In addition, the effects of all windows, sliding glass doors, inter-wall sill cracks, fuse boxes, pocket doors, etc., were measured.

For this series of measurements, the blower door was used to pressurize the apartment to 0.2-inch H_2O, and the corresponding total flow to produce this pressure difference was measured. Flows exiting through various leakage sources were then measured -- either by means of a Cenko linear velocity meter or a Cambridge Devices flow monitoring system. The Cenko meter was affixed to a cardboard plenum. The plenum was placed over various suspected leakage sources and the total flow occurring during one minute was noted. In a few cases, flow measurements were made using the Cambridge Devices flow monitoring system. In addition, several leakage sources were measured using both the Cambridge Devices flow measuring system and the Cenko linear velocity plus plenum system. These measurements demonstrated that both units agreed within a few (less than three) percent. In the extended Table V, the flows attributable to various leakage sources within Apartment No. 8121 are presented.

As a final test, the question of blower sensitivity was investigated. The blower/fan door combination was operated in such a manner so as to obtain a 0.2-inch H_2O positive differential pressure within the apartment. Various known leakage sources were sealed, and an attempt was made to see either a change in pressure or (correspondingly) a required change in flow in order to maintain a given pressure. It was concluded that the blower door was incapable of reproducibly sensing differences in flow of the order of 100 cubic feet per minute.

During the Fall of 1979, air leakage measurements by the tracer dilution method were also performed in selected apartments within each of the four sixplexes. Specifically, two apartments in each of these were measured by the tracer dilution method by techniques that have been documented in previous reports [15, 16]. Once again, the raw data are presented in Appendix A. In Table VI we summarize the leakage findings for Fall 1979. Note that the air leakage rates are standardized by the techniques of the previous report to meteorological conditions of 40°F temperature difference and 10 mph windspeed.

For the Fall 1980 measurement period only, three apartments were measured by the tracer dilution method. These were units which exhibited high, low, and average induced flowrates. The data are tabulated in Table VII.

Due to the lack of apparent change in measured flows in the 1980 data, the usefulness of air leakage measurements is limited. Previous work [17] has demonstrated that if measurable flow differences due to induced pressurization are absent, it is unlikely that air leakages inferred by the tracer dilution method will exhibit significant differences.

The last datum obtained in each of the Fall measurement periods, consisted of measuring the air leakage rate with the HVAC fan on, and with it off. Any significant difference in this rate must be due to duct leakage. Data for Apartment No.'s 8222 and 8709 are provided in Table VIII. For the purposes of energy conservation studies, it is probably more realistic to use air leakage data characterisitic of an apartment with the HVAC system operating.

TABLE I

INDUCED FLOWS - 1979

(All Flows in CFM at 0.2-inch H_2O)
N = Number of Air Changes at Indicated Pressure

APARTMENT NO.	FLOW	N
8165	1245	9.7
8164	1344	10.1
8163	1344	10.1
8162	1443	10.8
8161	1344	10.1
8160	1344	10.1
8153	1147	8.6
8152	1394	10.4
8151	1295	9.7
8150	1542	11.6
8149	1443	10.8
8148	1344	10.1
8135	1147	8.6
8134	1542	11.6
8133	1443	10.8
8132	1443	10.8
8131	1492	11.2
8130	1295	9.7
8123	1246	9.3
8122	1542	11.6
8121	1344	10.1
8120	1443	10.8
8119	1443	10.8
8118	1344	10.1

TABLE II

INDUCED FLOWS - 1980

(All Flows in CFM at 0.2-inch H_2O)
N = Number of Air Changes at Indicated Pressure

APARTMENT NO.	SINGLE BLOWER FLOW	N	DOUBLE BLOWER FLOW	TRIPLE BLOWER FLOW	CROSS FLOW (%)
8165 *	1414	10.6	1205	-	15
8164	1470	11.0	-	1260	14
8163	1605	12.0	-	1318	18
8162	1576	11.8	-	1319	16
8161	1619	12.1	-	1422	12
8160 *	1467	11.0	1262	-	14
8153 *	1309	9.8	1223	-	7
8152	1747	13.1	-	1467	16
8151	1356	10.2	-	1199	12
8150	1592	11.9	-	1213	24
8149	1582	11.9	-	1398	12
8148 *	1332	10.0	1239	-	7
8135 *	1111	8.3	1007	-	9
8134	1496	11.2	-	1233	18
8133	1569	11.8	-	1329	15
8132	1452	10.9	-	1325	9
8131	1385	10.4	-	1201	13
8130 *	1122	8.4	1046	-	7
8123 *	1441	10.8	1131	-	22
8122	1610	12.1	-	1273	21
8121	1598	12.0	-	1391	13
8120	1492	11.2	-	1334	11
8119	1458	10.9	-	1219	16
8118 *	1384	10.4	1110	-	20

* End Unit Apartment - Only One Adjacent Unit.

TABLE III

INDUCED FLOW IN APARTMENT AT 8709 O'CONNOR
WITH VARIOUS PARTS TAPED OVER
(Pressure = 0.2-inch H_2O)
N = Number of Air Changes at Indicated Pressure

CONDITION	FLOW (CFM)	N
Tape Heater & Return Ducts (Only)	1067	7.8
Tape Exhaust Fans (Only)	1117	8.2
Tape Dryer Vent (Only)	1217	9.0
Tape I.S. Sliding Door (Only)	1166	8.6
Tape I.S. Side Wall Joint	1067	7.8
Tape O.S. Wall Joint	1067	7.8
All Windows & Sliding Door, Heater Ducts, Exhaust Fan - Taped	665	4.9
Uncover All Windows	866	6.4
Uncover Sliding Door and Window	866	6.4
Uncover Dryer Vent	916	6.7
Uncover Ducts	1166	8.6
No Tape	1217	9.0

TABLE IV

INDUCED FLOW IN APARTMENT AT 8222 O'CONNOR
WITH VARIOUS PARTS TAPED OVER

(Pressure = 0.2-inch H_2O)
N = Number of Air Changes at Indicated Pressure

CONDITION	FLOW (CFM)	N
All Taped	901	6.8
Remove Tape from Wall Switches, Sockets, and Plumbing	999	7.5
Remove Tape from West Inside Wall Joint	1044	7.9
Remove Tape from East Inside Wall Joint	1147	8.6
Remove Tape from Kitchen Vent	1147	8.8
Remove Tape from Bathroom Vent	1246	9.3
Remove Tape from Dryer Vent	1270	9.5
Remove Tape and Cover from Crawl Space Penetrations	1344	10.1
Remove Tape from Outside Wall Joint	1344	10.1
Remove Tape from All Other Ducting	1591	11.4
Remove Tape and Cover from Sliding Glass Door	1616	12.1
All Tape Removed	1616	12.1

TABLE V

DETAILED INDUCED FLOWS IN APARTMENT AT 8121 O'CONNOR
(Pressure = 0.2-inch H_2O)

CONDITION	FLOW (CFM)	COMMENTS
Dryer Vent	61	
Kitchen Vent Fan	101	Vent Shutters Open
Kitchen Vent Fan	34	Vent Shutters Held Closed
110V Outlet - Dryer Room	6	
220V Outlet - Dryer Room	-	
First Floor Bath Ceiling Vent	50	
West Living Room Wall Outlet	-	
Southwest Living Room Wall Outlet	-	
East Living Room Wall Outlet	-	
Northeast Living Room Switch	-	
Thermostat	-	
Northeast Living Room Outlet	-	
North Dining Area Switch	-	Cover Plate In Place
North Dining Area Switch	9	Cover Plate Removed
North Living Room Switch	-	
Northwest Living Room Wall Outlet	-	
Southeast Living Room Switch	-	Cover Plate In Place
Southeast Living Room Switch	13	Cover Plate Removed
Southeast Living Room Wall Outlet	-	Cover Plate In Place
Southeast Living Room Wall Outlet	21	Cover Plate Removed
Duct Into Dining Area	23	
North Kitchen Wall Switch	-	
West Duct Into Living Room	17	
East Duct Into Living Room	??	Couldn't Measure Due to Duct Position

TABLE V (CONTINUED)
DETAILED INDUCED FLOWS IN APARTMENT AT 8121 O'CONNOR
(Pressure = 0.2-inch H_2O)

CONDITION	FLOW (CFM)	COMMENTS
Southwest Kitchen Wall Outlet	1	
Northwest Kitchen Wall Switch and Outlet	-	
Lower Hallway Switch	-	
Kitchen Island Outlet	-	
Kitchen Island Phone Jack	-	
Kitchen Duct	10	
Pantry Switch	Trace	Less than 1 CFM
Pantry Bell	-	
South Wall Kitchen Outlet	-	
East Wall Dryer Switch	-	
First Floor Bathroom Switch	3	
South Wall Kitchen Island Switch	-	
East Wall Dining Area Outlet	-	
North Wall Dining Area Outlet	-	
A/C Intake on Stairs	39	
Fuse Box	30	
Crawl Hatch	28	
Lower Pocket Door	101	
2nd Floor Hall/South Wall Switch	6	
2nd Floor Bathroom Switch	10	
2nd Floor Bathroom Duct	11	
2nd Floor Bathroom Ceiling Fan	61	
2nd Floor Ceiling Light/South	4	
2nd Floor Ceiling Light/North	??	Couldn't Measure Due to Location
2nd Floor West Wall/Hall Outlet	-	

TABLE V (CONTINUED)

DETAILED INDUCED FLOWS IN APARTMENT AT 8121 O'CONNOR

(Pressure = 0.2-inch H_2O)

CONDITION	FLOW (CFM)	COMMENTS
Northwest Bedroom/South Wall Switch	-	
Northwest Bedroom/South Wall Outlet	-	
Northwest Bedroom/West Wall Phone Jack	4	
Northwest Bedroom/West Wall Outlet	6	
Northwest Bedroom/North Wall Outlet	-	
Southwest Bedroom/North Wall Switch	-	
Southwest Bedroom/North Wall Outlet	-	
Southwest Bedroom/West Wall Phone Jack	-	
Southwest Bedroom/West Wall Outlet	-	
Southwest Bedroom/South Wall Outlet	2	
Southwest Bedroom/East Wall Outlet	2	
Southeast Bedroom/North Wall Switch	-	
Southeast Bedroom/East Wall Phone Jack	3	
Southeast Bedroom/East Wall Outlet	-	
Southeast Bedroom/North Wall Outlet	-	
Southeast Bedroom/West Wall Outlet	Trace	Less Than 1 CFM
Living Room Ceiling Light Fixture	-	
Dryer Room Light Fixture	-	
Kitchen Ceiling Light Fixture	-	
Dining Room Ceiling Light Fixture	Trace	Less Than 1 CFM
Kitchen Window	25	
Northwest Bedroom Window	19	
Southwest Bedroom Window	22	
Southeast Bedroom Window	20	
2nd Floor Bathroom Medicine Chest	20	
Sliding Glass Door	99	

TABLE VI

AIR LEAKAGE RATES MEASURED BY TRACER DILUTION
FOR SELECTED APARTMENTS DURING FALL 1979

Apartment No.	Air Leakage Rate *	V (mph)	T (°F)	Air Leakage Rate **	Average Air Leakage Rate **
8165 (A.M.)	0.80	7.5	37	0.98	1.20
8165 (P.M.	0.69	3.	32	1.41	
(12/3/79)					
8162 (A.M.)	0.96	9.5	37	1.00	0.98
8162 (P.M.)	0.77	7.8	26	0.96	
(12/4/79)					
8148 (A.M.)	0.73	7.5	38	0.89	1.13
8148 (P.M.)	0.68	3.	34	1.37	
(12/3/79)					
8151 (A.M.)	0.93	9.3	37	0.99	0.88
8151 (P.M.)	0.61	7.8	26	0.76	
(12/4/79)					
8133 (A.M.)	-	-	-	-	0.72
8133 (P.M.)	0.57	8.	19	0.72	
(12/4/79)					
8130 (A.M.)	0.58	7.5	40	0.70	0.96
8130 (P.M.)	0.61	3.	36	1.22	
(12/3/79)					
8123 (A.M.)	-	-	-	-	1.43
8123 (P.M.)	0.73	3.	39	1.43	
(12/3/79)					
8121 (A.M.)	0.76	9.3	30	0.83	0.75
8121 (P.M.)	0.52	7.8	19	0.67	

* Air leakage rate at measured wind speed and temperature.

** Air leakage rate at wind speed of 10 mph and temperature difference of 40°F.

TABLE VII

AIR LEAKAGE RATES MEASURED BY TRACER DILUTION FOR SELECTED APARTMENTS DURING FALL 1980

Apartment No.	Air Leakage Rate *	V (mph)	T (°F)	Air Leakage Rate **	Average Air Leakage Rate **
8152 (A.M.)	0.63	2.5	13	1.29	1.64
8152 (P.M.) (10/22/80)	0.59	1.5	5	1.98	
8134 (A.M.)	0.85	2.5	13	2.10	1.96
8134 (P.M.) (10/22/80)	0.47	1.	4	1.81	
8135 (A.M.)	0.73	2.5	13	1.86	2.14
8135 (P.M.) (10/22/80)	0.63	1.	4	2.42	

* Air leakage rate at measured wind speed and temperature.

** Air leakage rate at wind speed of 10 mph and temperature difference of 40°F.

TABLE VIII

COMPARISON OF AIR LEAKAGE RATES MEASURED BY TRACER DILUTION WITH THE HVAC SYSTEM ON OR OFF

Apartment No. 8222

CONDITION	WIND SPEED (mph)	T (°F)	Air Leakage Rate*	Air Leakage Rate**
HVAC Fan On	14.3	33	0.85	0.66
HVAC Fan Off	14.	34	0.63	0.50

Apartment No. 8705

CONDITION	WIND SPEED (mph)	T (°F)	Air Leakage Rate*	Air Leakage Rate**
HVAC Fan On	9.5	4	0.62	0.73
HVAC Fan Off	8.8	3	0.40	0.50

* Air leakage rate at measured wind speed and temperature.

** Air leakage rate at wind speed of 10 mph and temperature difference of 40°F.

4. DISCUSSION

One of the most striking results of detailed pressurization measurements occurs in two apartments (8222 and 8709), which show a total leakage reduction of over 40 percent by merely blocking off leakage sources with tape and/or builders plastic. In Table IX we document the induced flows in these two apartments before and after extensive sealing utilizing tape and builders plastic.

The purpose of a test like this is to show the potential reduction in leakage which is obtainable if major sources of leakage are amenable to sealing of some sort. Note that on this table the percentage reduction achieved is actually higher than that shown since the induced flow Apartments 8222 and 8709 does not have the cross-apartment leakage flow subtracted out. At the time these measurements were made only a single blower was available. Consequently, it was not possible to measure the induced flow corresponding to leakage from this apartment to the outside environment and not to adjacent apartments.

The detailed measurements of flow leakage in Apartment No. 8121, which were documented in Table V, are re-cast in Table X. It more particularly points out the magnitude of leakage attributable to the various components and structural features of this apartment. If each of these components and structural features could be maintained leak-free, then the percentage reduction shown in Table X is attainable. Note, however, that leakage reduction of this magnitude may not be practical from an economic or building standpoint.

Data such as these, however, are useful in pointing out the magnitude of the leakage attributable to various components and structural features of the apartment, and should suggest areas in which attention to detail during the construction process or rudimentary sealing after construction could yield a substantial decrease in air leakage which would result in energy cost reduction.

TABLE IX

SUMMARY OF INDUCED FLOW MEASUREMENTS
IN APARTMENTS 8222 and 8707
(Pressure = 0.2-inch H_2O)

Apartment No.	Induced Flow*	Induced Flow**	% Reduction
8222	1616 CFM	910 CFM	44
8709	1217 CFM	665 CFM	45

* Includes cross-apartment leakage.

** All joints, windows, sliding doors, and ducts are taped.

TABLE X

SUMMARY OF FLOWS IN APARTMENT 8121

Description	Flow (CFM)	
Induced Flow @ 0.2-inch H_2O	1701	
Cross-Apartment Leakage	(220)	
Net Induced Flow to Outside	1480	
Total Induced Leakage of Components from Table III		809
Measured Inside Wall/Floor Joint Leakage		100
Total Identified Induced Leakage		909

Potential Reduction = (1480 - 909)/1480 = 61%

To further emphasize both the magnitude of potential reduction represented by the various leakages measured in Apartment No. 8121, as well as to graphically illustrate the magnitude of the leakages attributable to various structural features and building components, the leakage data presented in Table V has been graphically depicted on Figure 4. Note that in any discussion of air leakage losses for energy conservation, the cross-apartment leakage does not bear directly on the question of energy consumption.

Note that included in the data given in the tables is included a calculated "N" value. This "N" is interpreted as the air exchange rate within the structure at the given pressure difference. The "N" values range from 8.5 to 12 for these apartments. A 50 percent reduction would result in a range of 4.2 to 6. This is not out of the realm of the "doable". In fact, we should note that the new Swedish building standard requires "N" for new residential structures to be 3.

An interesting observation on flow measurements within Apartment No. 8121 was that the fiberglass wall-covering system was lapped into electrical wall penetrations in such a way that when the cover plate was attached a good seal was obtained. Reference to Table V shows several cases in which flow measurements were made on electrical penetrations -- both with the cover plate on and the cover plate off. In most cases, the flow was "zero" or negligible when the cover plate was in place. Flow through these penetrations without the cover plate, however, was non-negligible. It is well-known that these electrical penetrations are sources of considerable leakage within residential structures. It is interesting that the fiberglass wall-covering system, in conjunction with the standard electrical cover plates, resulted in a dramatic reduction of the leakage.

As expected, windows, vent fans, and the sliding door provided the majority of the induced air leakage within the apartment. By conventional standards, the windows are rather leaky. For a 3-foot by 5-foot,

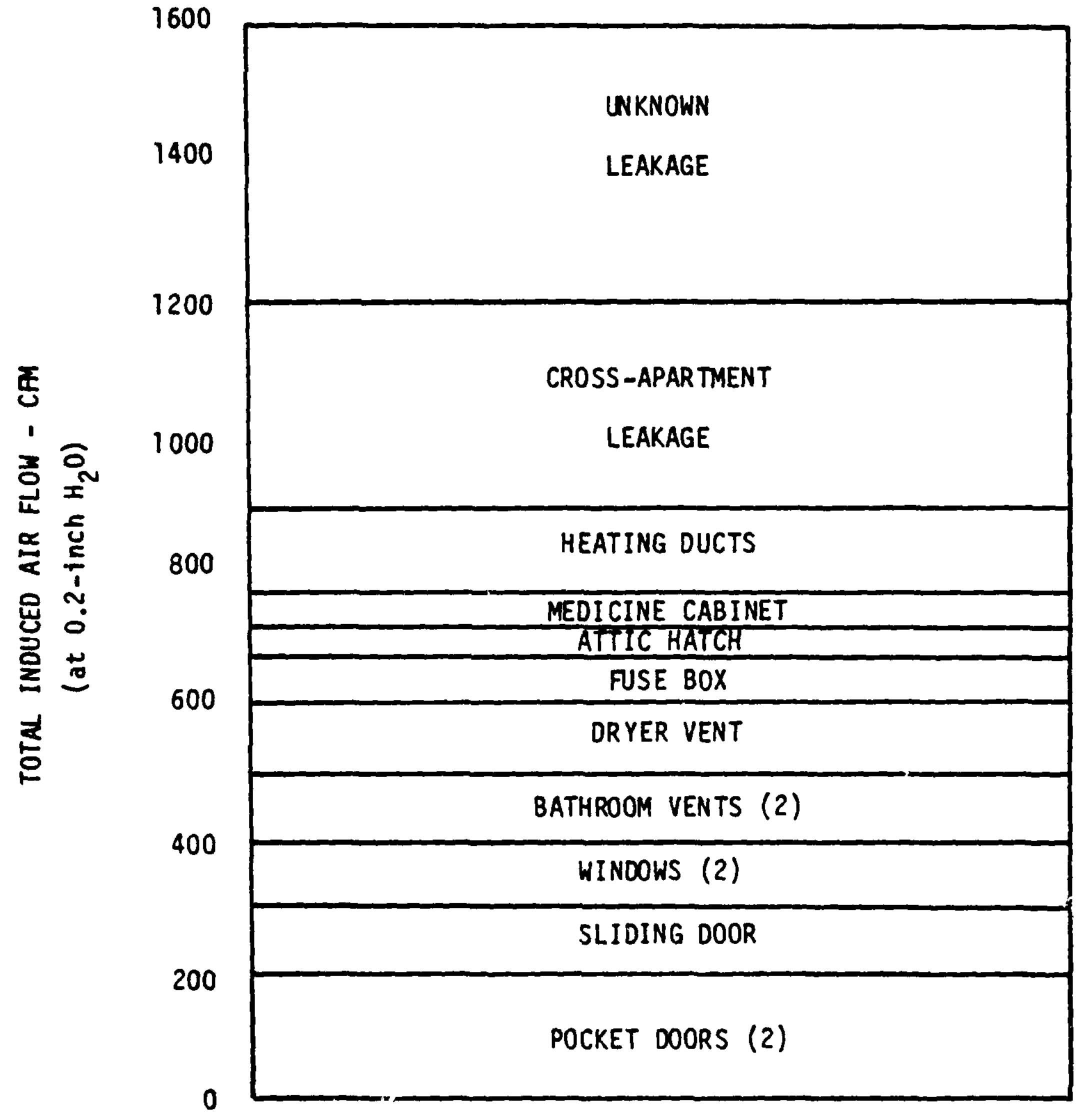

Figure 4. Component Air Leakages at Willoughby Bay Apartments.

aluminum frame, single slide window such as in the kitchen, a field-measured leakage averaging approximately 1.0 CFM/foot of sash crack is typical [18], while the manufacturers specifications average roughly 0.5 CFM/foot of sash crack. For the kitchen window in Apartment No. 8121, the corresponding leakage is in excess of 2.9 CFM/foot of sash crack. The other sliding windows within the apartment are not much better. Clearly window leakage is significantly higher than either typical field measurement or manufacturer's standards.

Other significant sources of air leakage include the sliding glass door, the upstairs and downstairs pocket doors, the kitchen vent, the crawl space, and the wall penetration for the bathroom medicine chest.

Clearly, in any retrofitting program, sealing or complete elimination of these leakage sources must be undertaken.

So far as the utility of using a fan door for on-site pressurization work, after an initial period of familiarization, it was found that a two-man crew can perform a complete pressurization/evacuation test in adjacent apartments in times ranging from 35 to 45 minutes. It should be emphasized, however, that if routine pressurization activities are contemplated, an engineering re-design of the blower door should be undertaken, with an eye toward human engineering factors.

For detailed measurements, such as are required for retrofitting programs, the blower doors should be used in conjunction with a lower-range flow measuring system. The blower door can be used to provide pressurization at some constant flowrate, while measuring systems capable of responding to flows between 1 CFM and 100 CFM can be used to quantify the contribution of the various leakage sources of interest. Also, use of a more sensitive differential pressure transducer with the blower door might permit corrections of low-flow leakage sources to be noted and quantified directly with the blower door instrumentation.

Smoke pencils were found to be useful in finding leaks that could not be enclosed by the low-flowrate instrument plenum (such as baseboard cracks), and for determining that the leaks were corrected.

5. CONCLUSIONS AND RECOMMENDATIONS

On the basis of measurement and observations obtained over a three-year period at four selected sixplexes within the Willoughby Bay housing complex at Norfolk, Virginia, the following conclusions can be drawn.

- No reductions in air leakage could be measured by the blower door from the retrofits applied to Buildings 108, 110, and 112. It seems logical, however, that some small improvement was made but was masked by instrument sensitivity and the existence of large, uncorrected leakage areas. Measurements were in accordance with ASTM E774-81.
- Potential leakage reductions of slightly less than 50 percent are possible by either simple sealing-type retrofits or component replacement.
- Leakage reductions of this magnitude within individual apartments would not result in overly tight structures.
- The fiberglass mat plus mastic system applied to an entire wall, in conjunction with standard electrical cover plates, appears to eliminate electrical penetration leakage. Leakage could also reportedly be eliminated with inexpensive ($0.05 each) plastic inserts.
- The blower door pressurization technique could not reliably sense flow changes induced by simulated retrofitting of less than 100 CFM at 0.2-inch H_2O pressure.
- The blower door, coupled with low flow range measurement devices, provides a means to investigate leakage sources as small as 1 CFM.
- Collection of energy consumption data from the heating system should continue until September 1982, and all HVAC energy data collected since the project was initiated be analyzed to determine if energy savings are being made from the retrofits.

A few apartments within the four sixplexes measured should be permanently retrofitted against air leakage at the locations discussed in Table V. In some cases, simple sealing will suffice; in others, replacement of existing features (such as sliding glass doors) should be undertaken. Pressurization tests can be used to document actual leakage reductions attained.

Monitoring energy consumption in these apartments, and comparing it to that in unretrofitted adjacent apartments (in conjunction with available historical energy consumption data), will provide a measure of the actual utility of retrofitting apartment units. It will also provide the basis for performing economic analyses of retrofitting.

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APPENDIX A

AIR LEAKAGE CURVES FOR TWENTY-FOUR APARTMENT UNITS
NORFOLK, VIRGINIA

In this Appendix, the measured blower door data for the twenty-four apartment units are presented. Curves obtained for each unit before and after retrofit are presented. In a few cases, data are also presented for flows obtained with the blower door assembly installed opposite to its normal installation direction. These data are denoted as "reversed." All data labeled "before" were obtained during the period from November 27 through December 4, 1979. All data denoted by "after" were measured during the period from October 14 through October 23, 1980.

LIST OF FIGURES - APPENDIX A

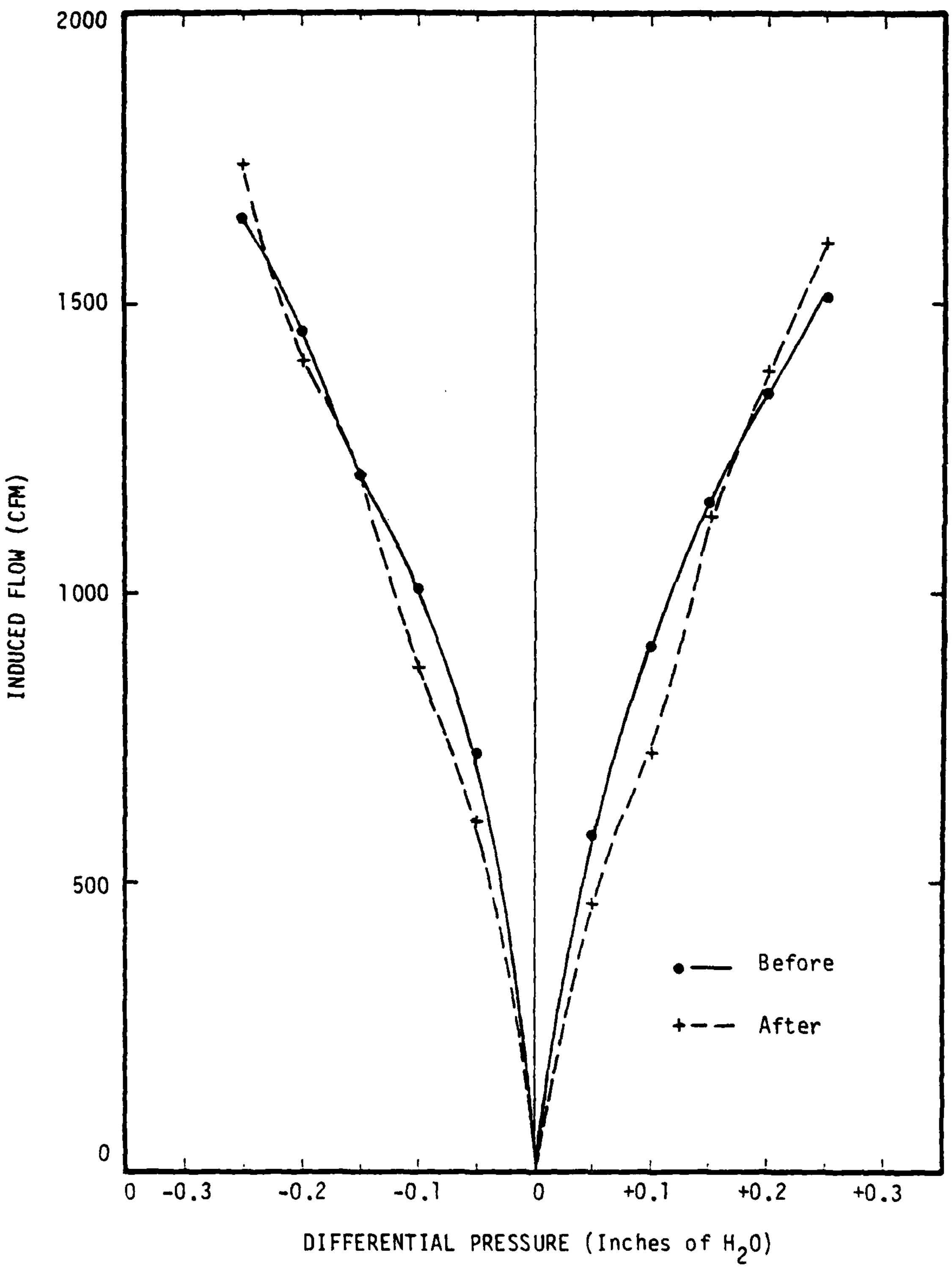

Figure A.1 Induced Flow <u>versus</u> Pressure for Apartment No. 8118.

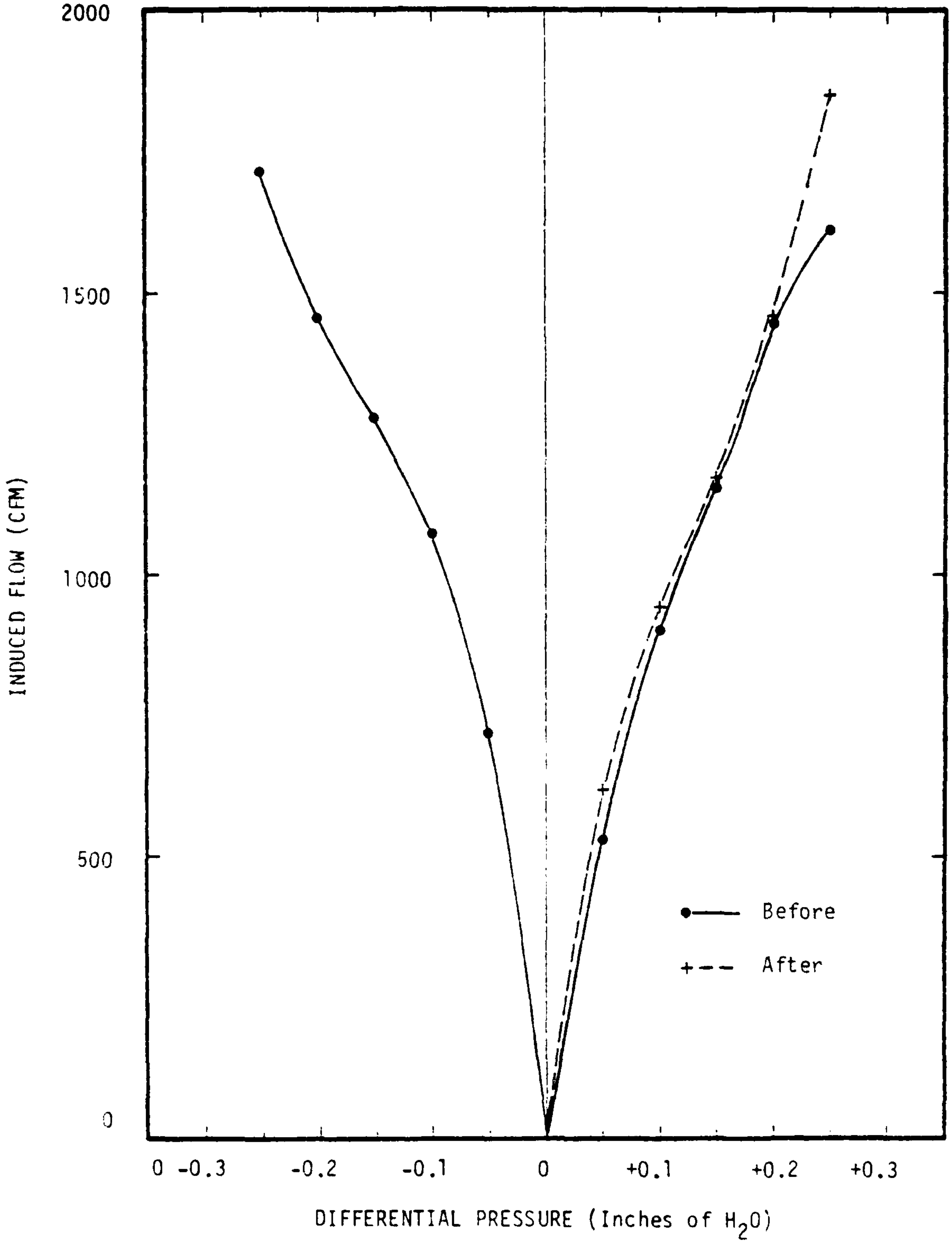

Figure A.2 Induced Flow *versus* Pressure for Apartment No. 8119.

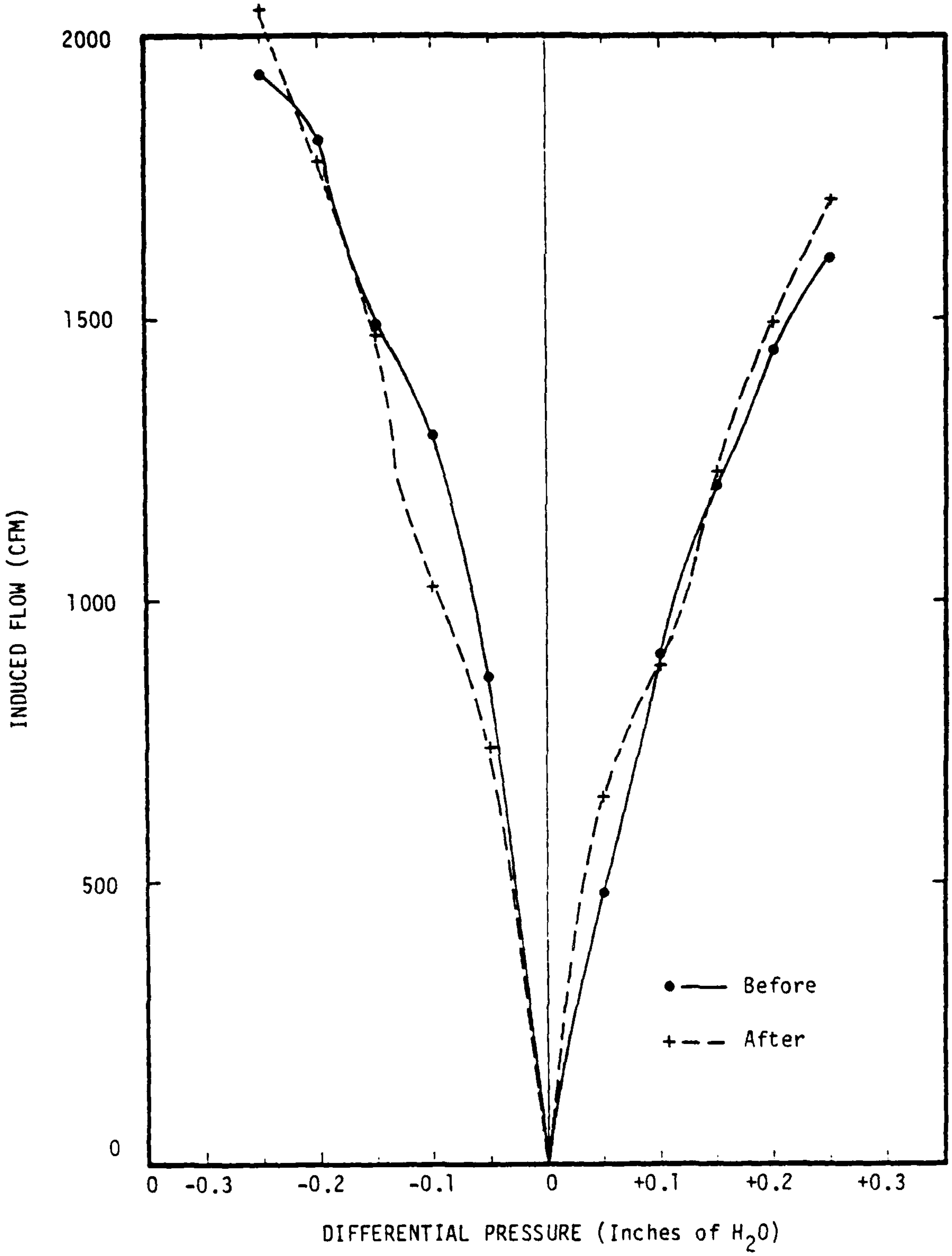

Figure A.3 Induced Flow versus Pressure for Apartment No. 8120.

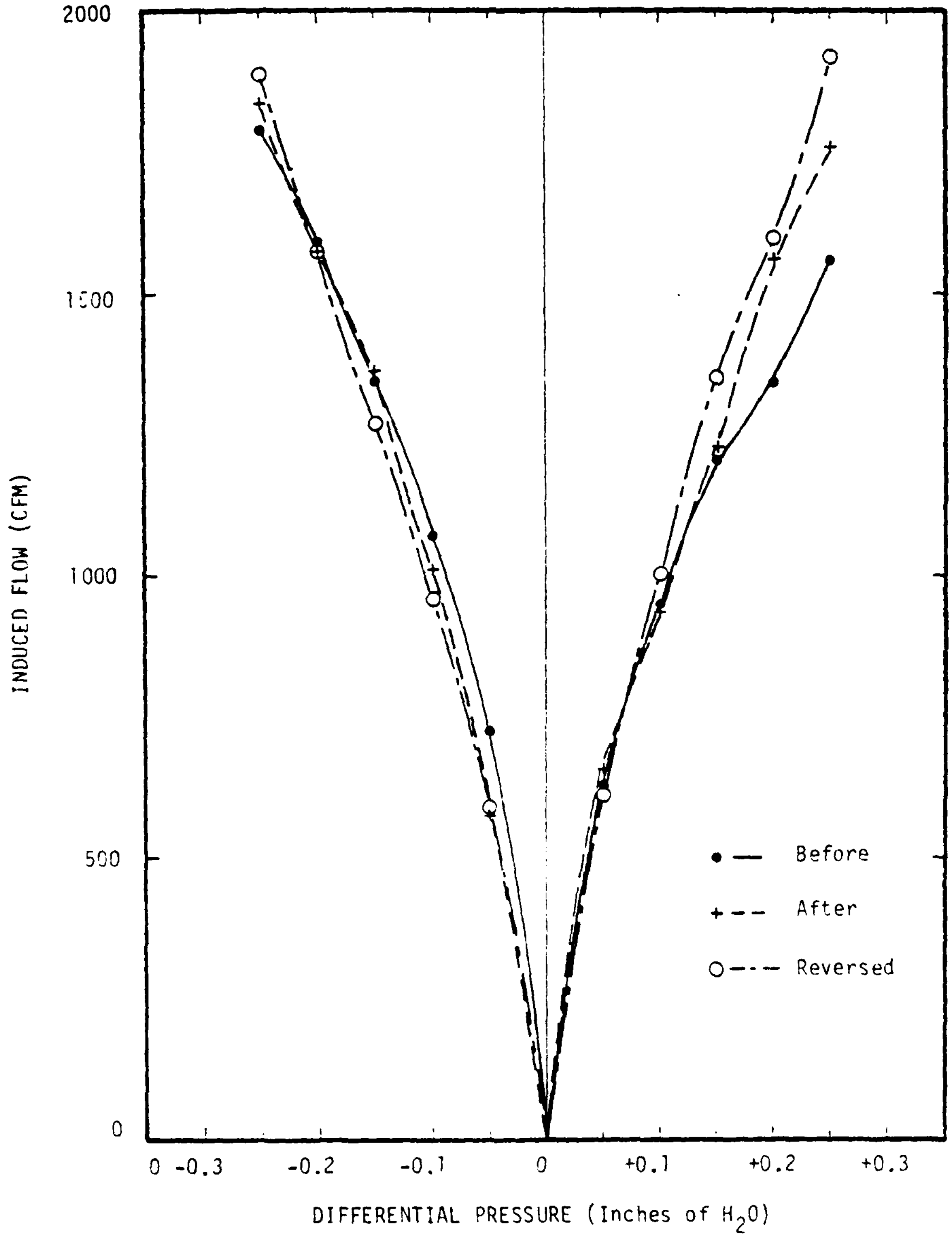

Figure A.4 Induced Flow versus Pressure for Apartment No. 8121.

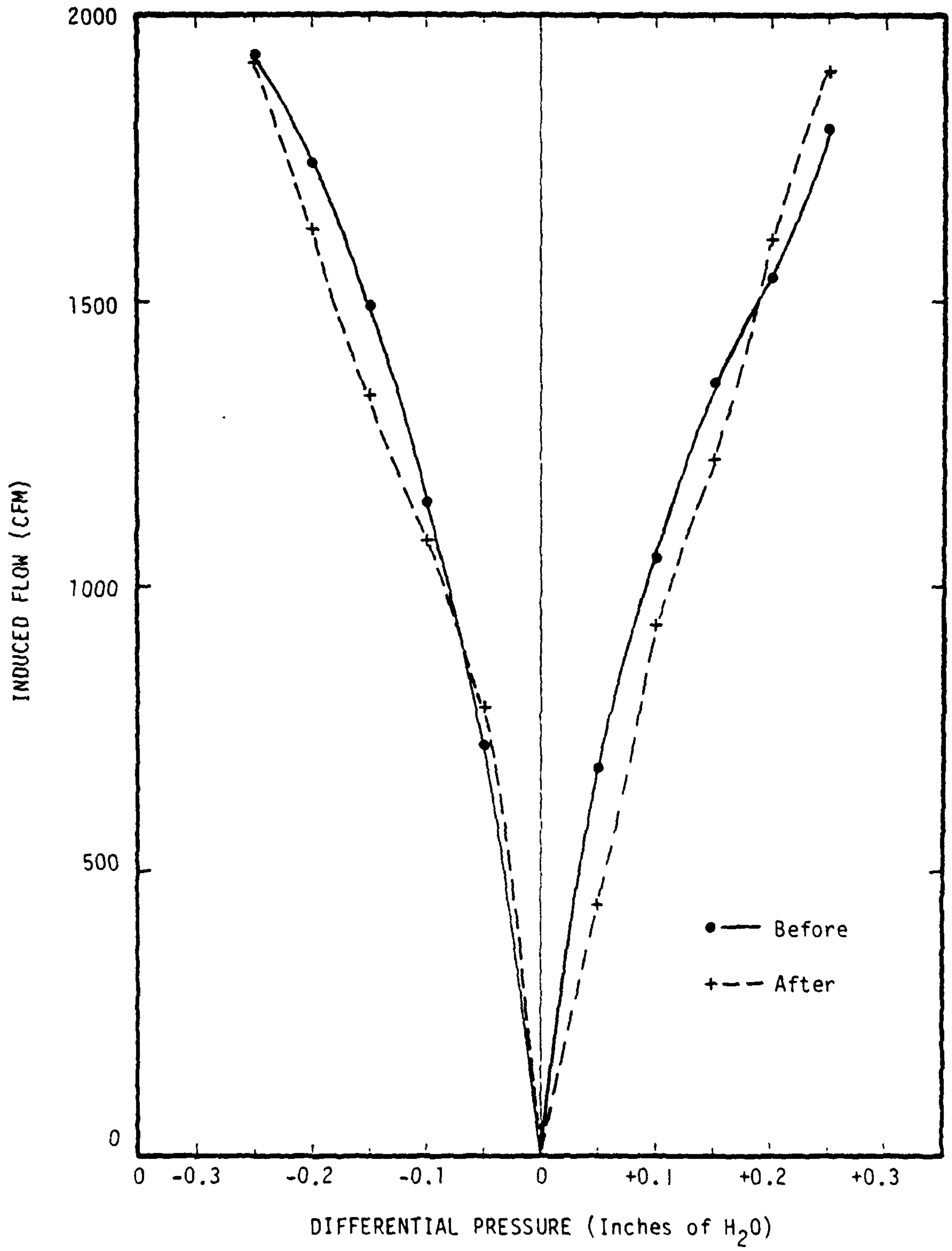

Figure A.5 Induced Flow versus Pressure for Apartment No. 8122.

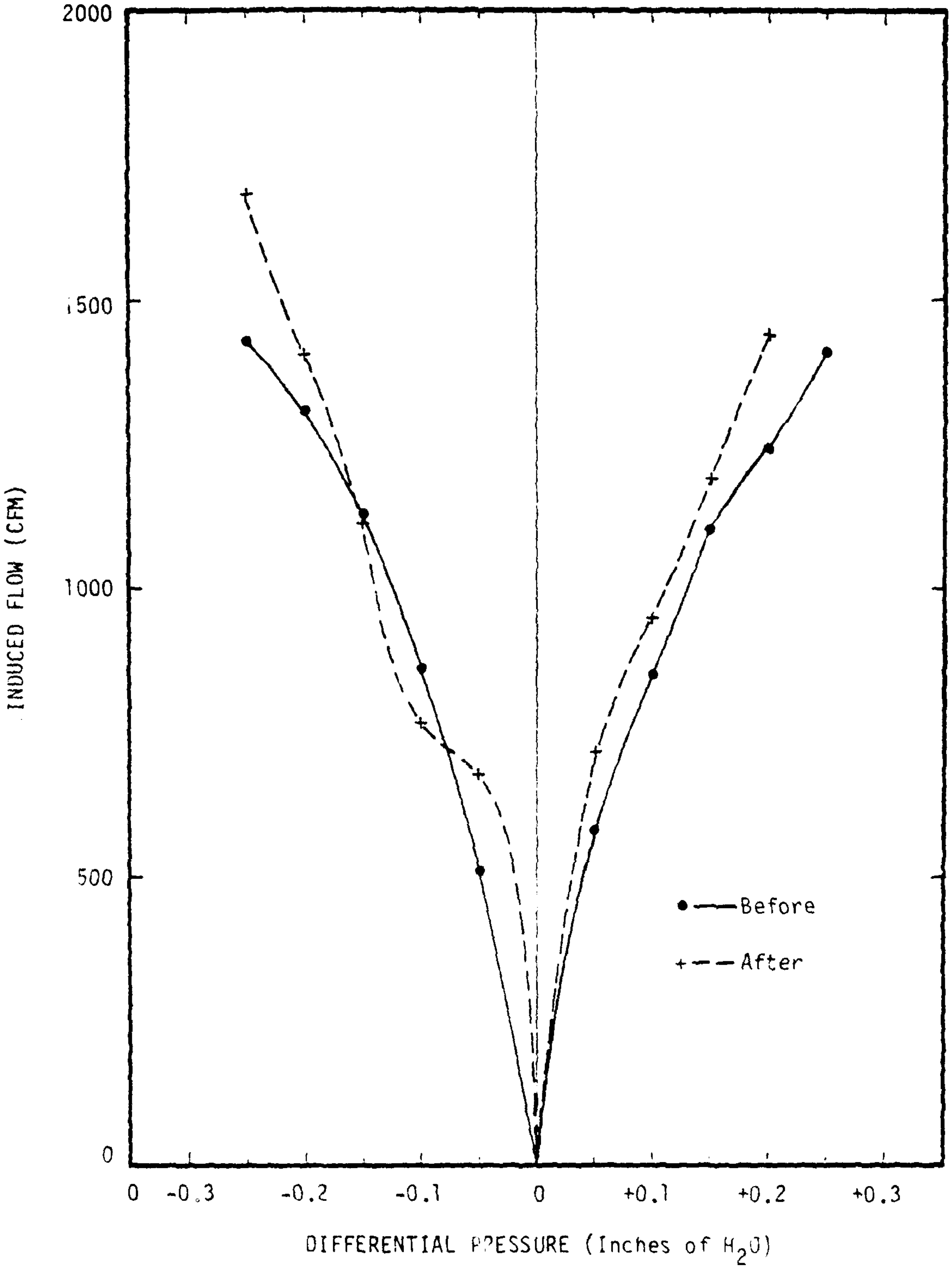

Figure A.6 Induced Flow versus Pressure for Apartment No. 8123.

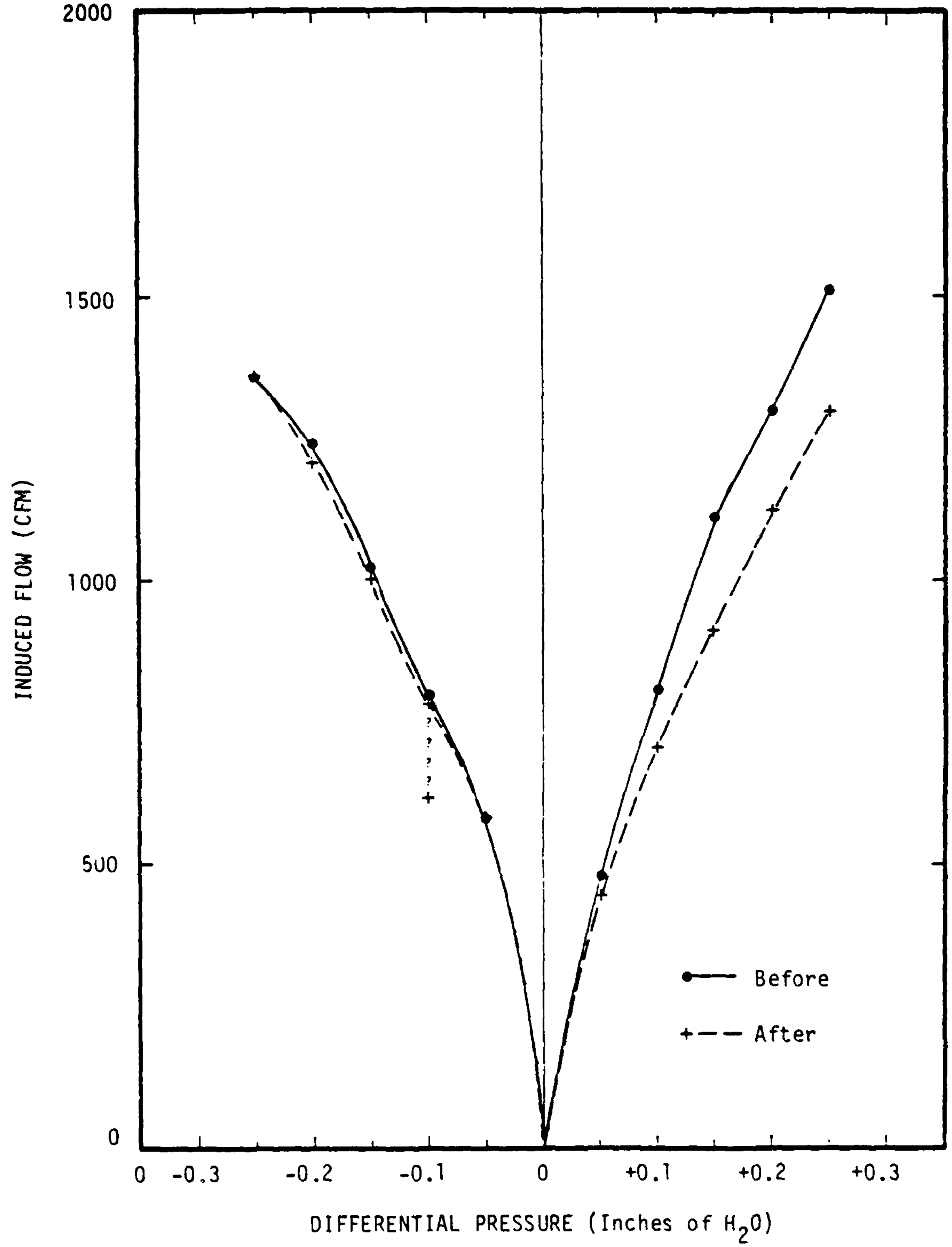

Figure A.7 Induced Flow *versus* Pressure for Apartment No. 8130.

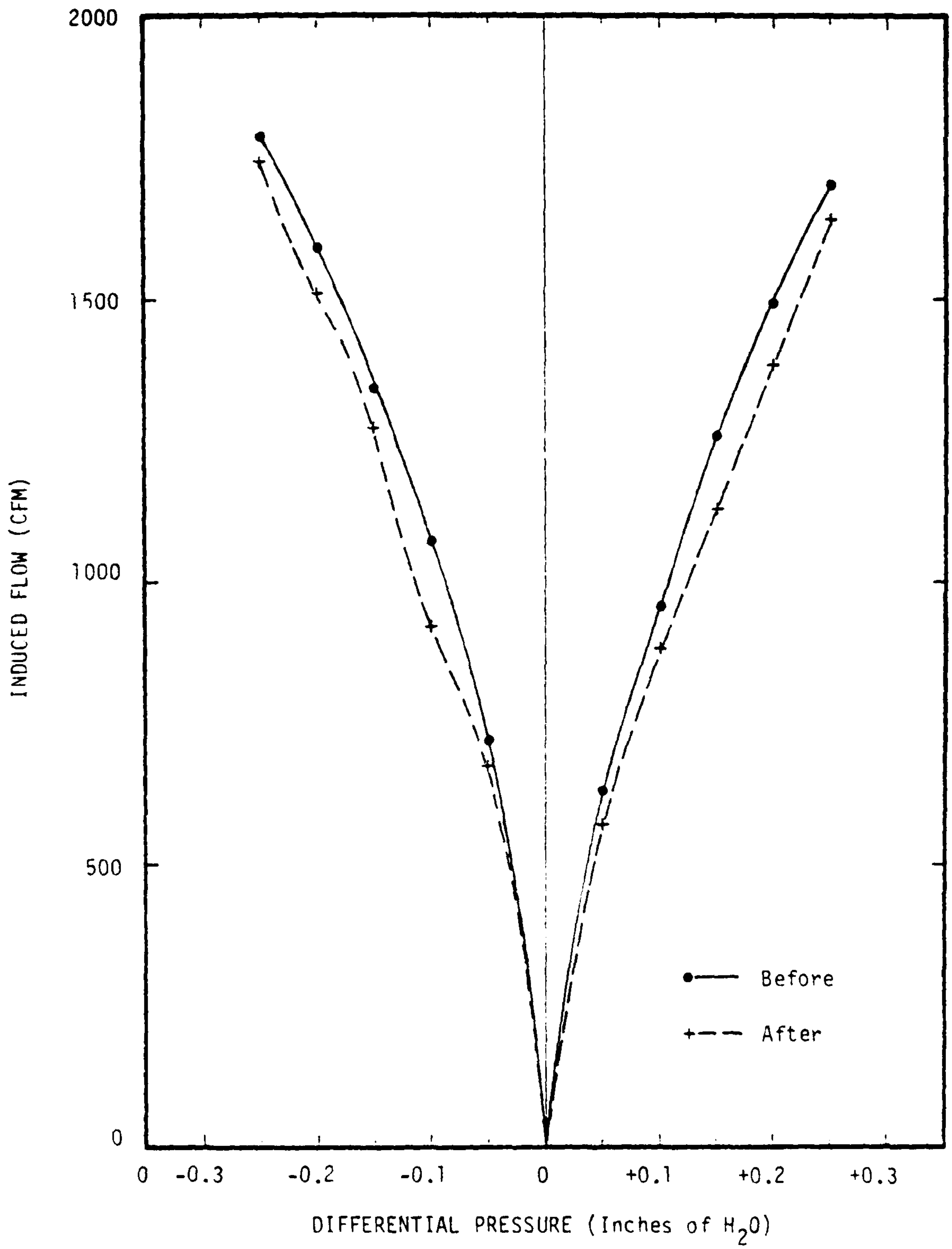

Figure A.8 Induced Flow versus Pressure for Apartment No. 8131.

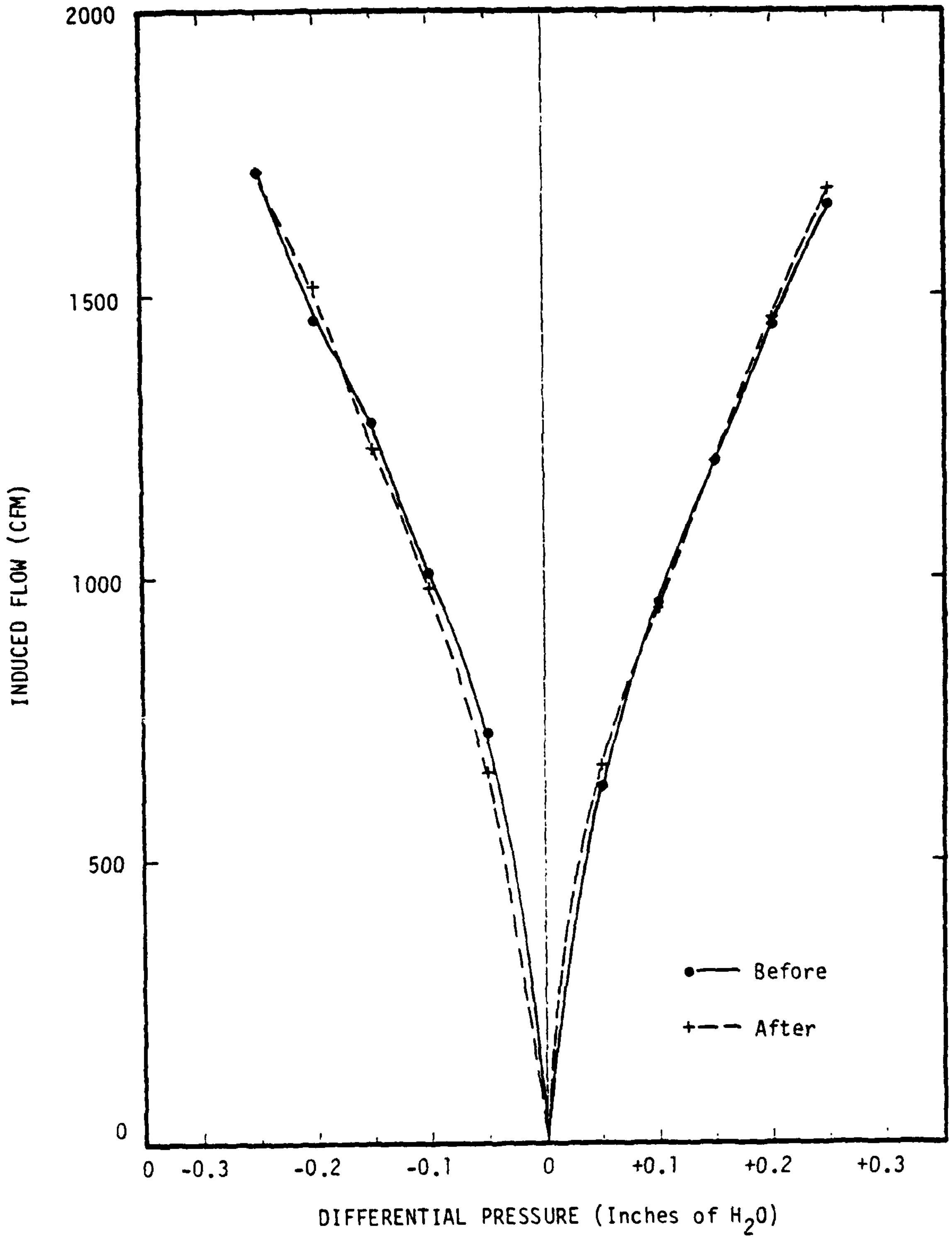

Figure A.9 Induced Flow <u>versus</u> Pressure for Apartment No. 8132.

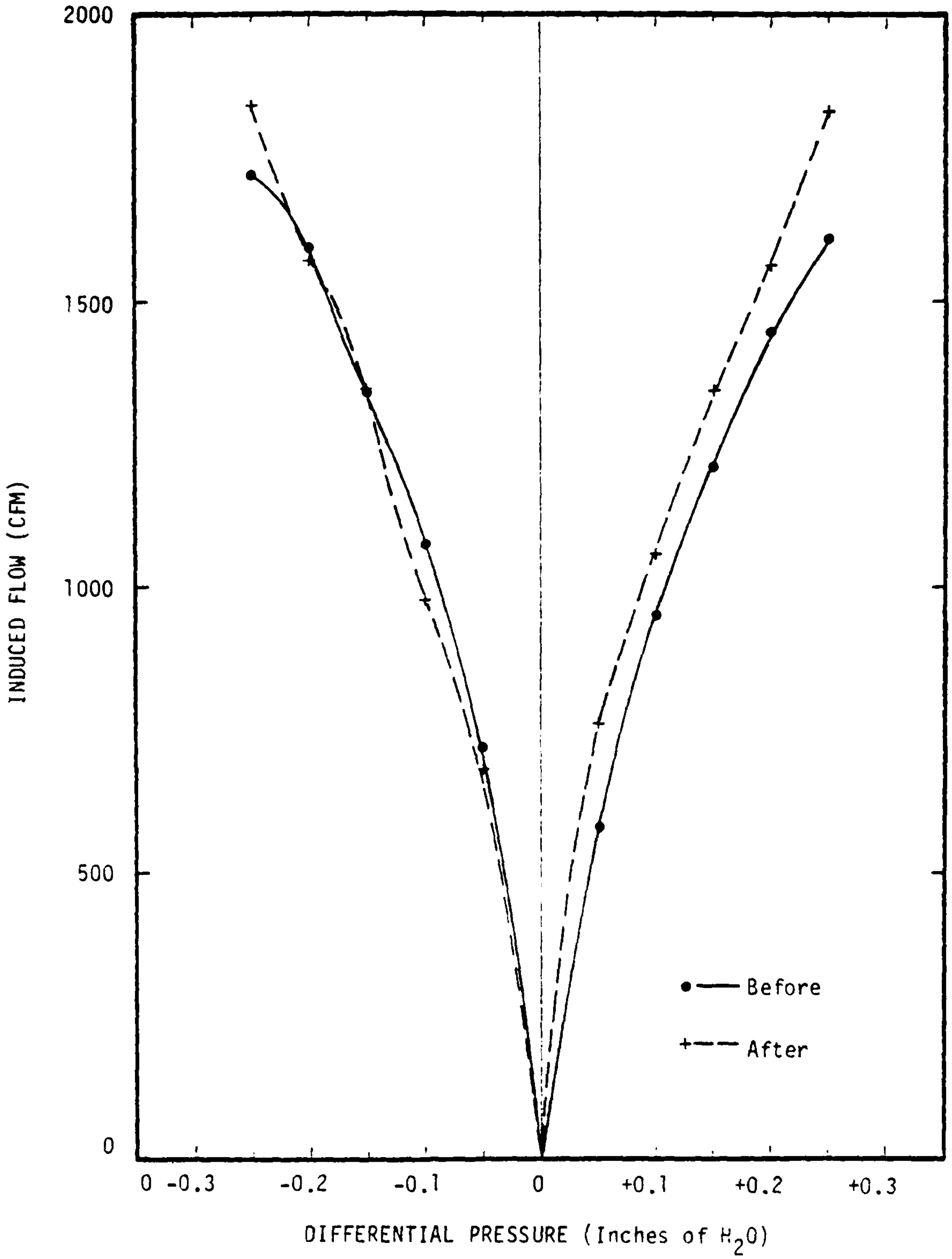

Figure A.10 Induced Flow versus Pressure for Apartment No. 8133.

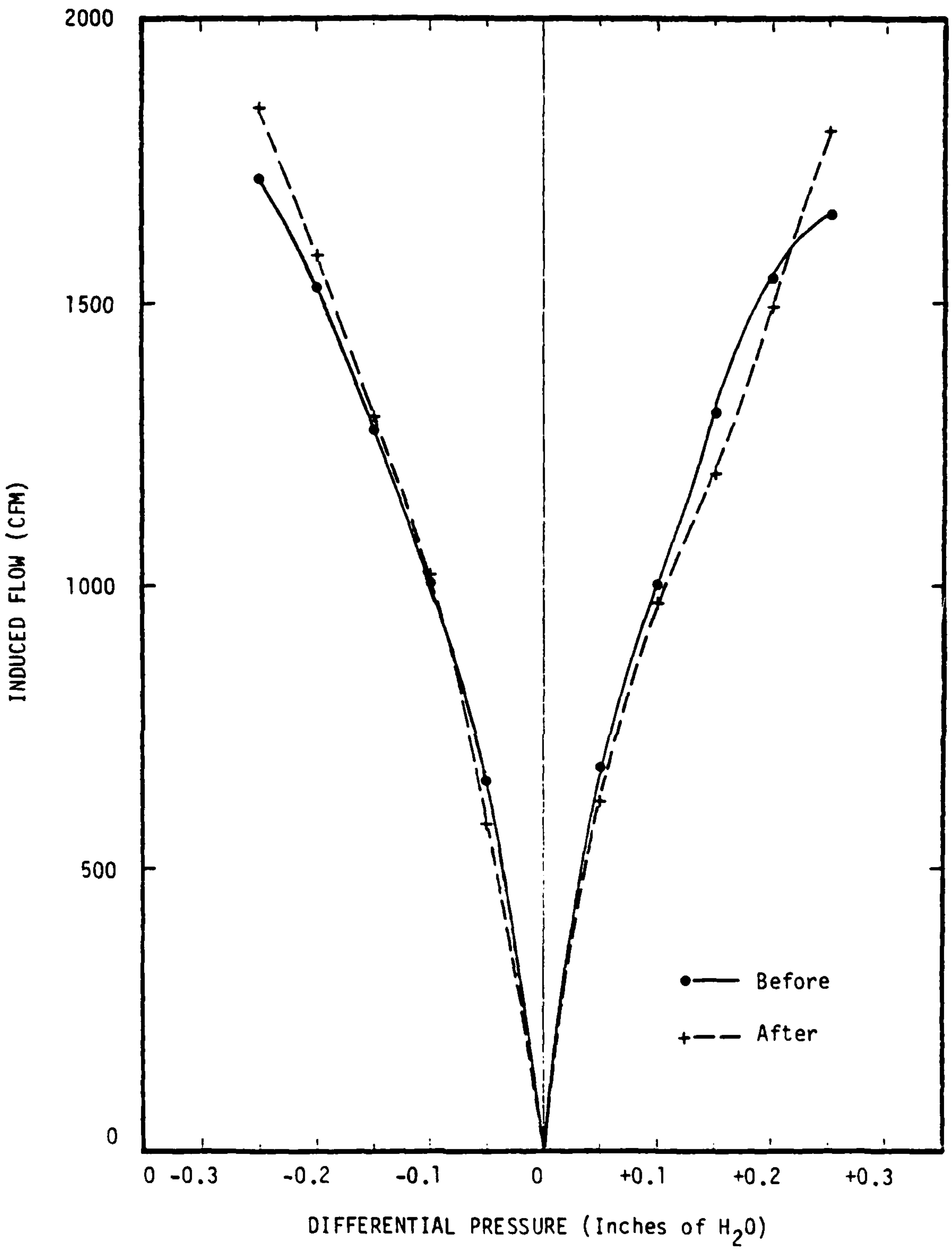

Figure A.11 Induced Flow versus Pressure for Apartment No. 8134.

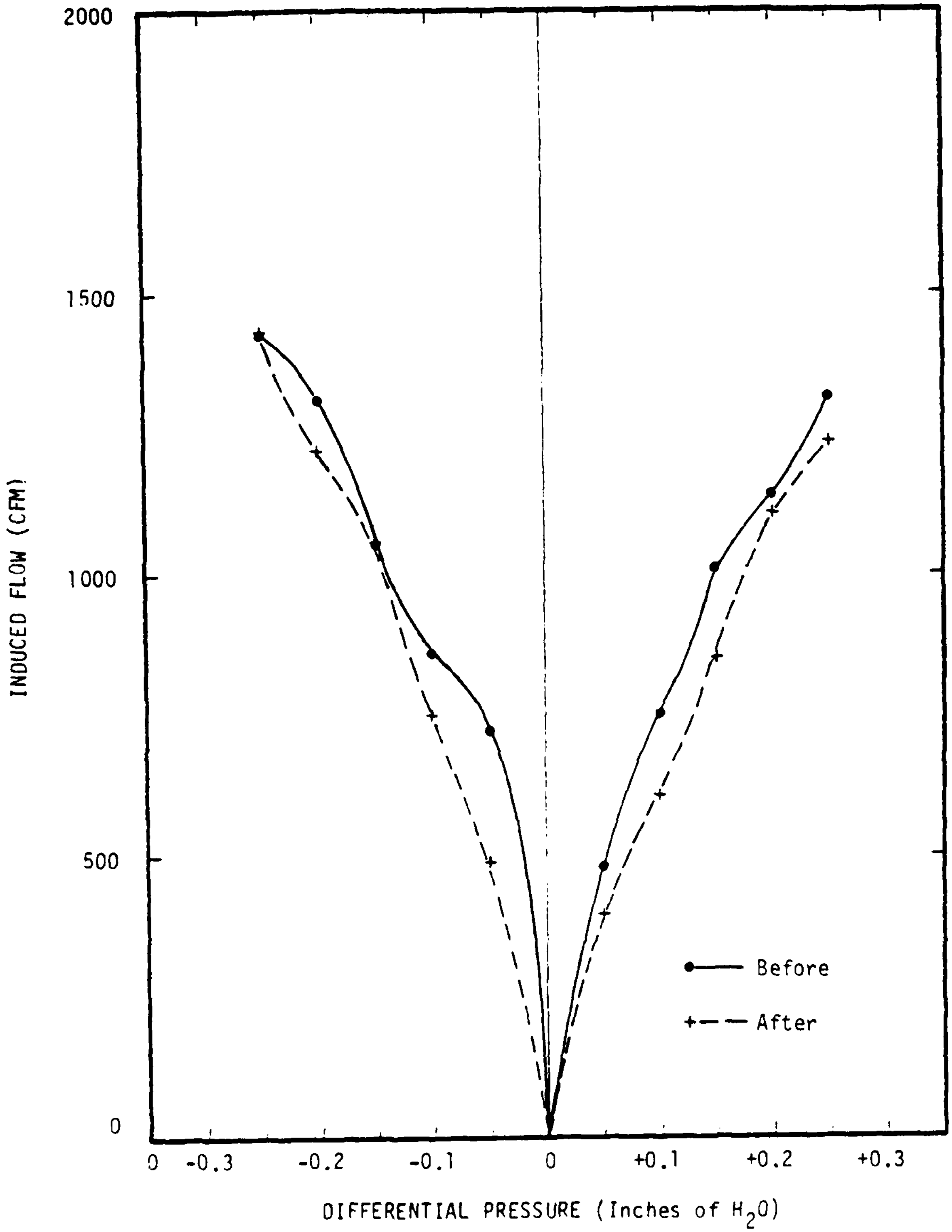

Figure A.12 Induced Flow versus Pressure for Apartment No. 8135.

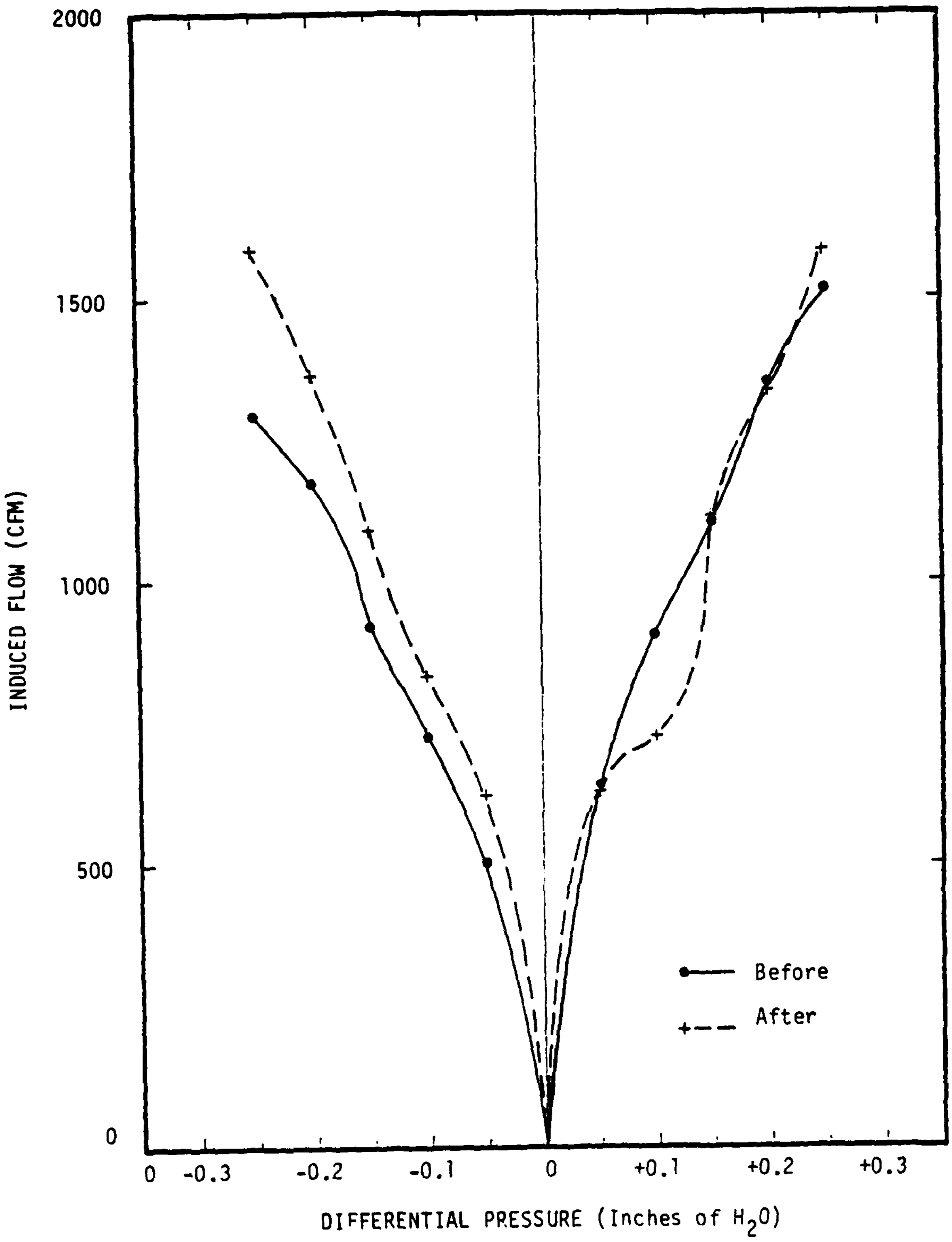

Figure A.13 Induced Flow *versus* Pressure for Apartment No. 8148.

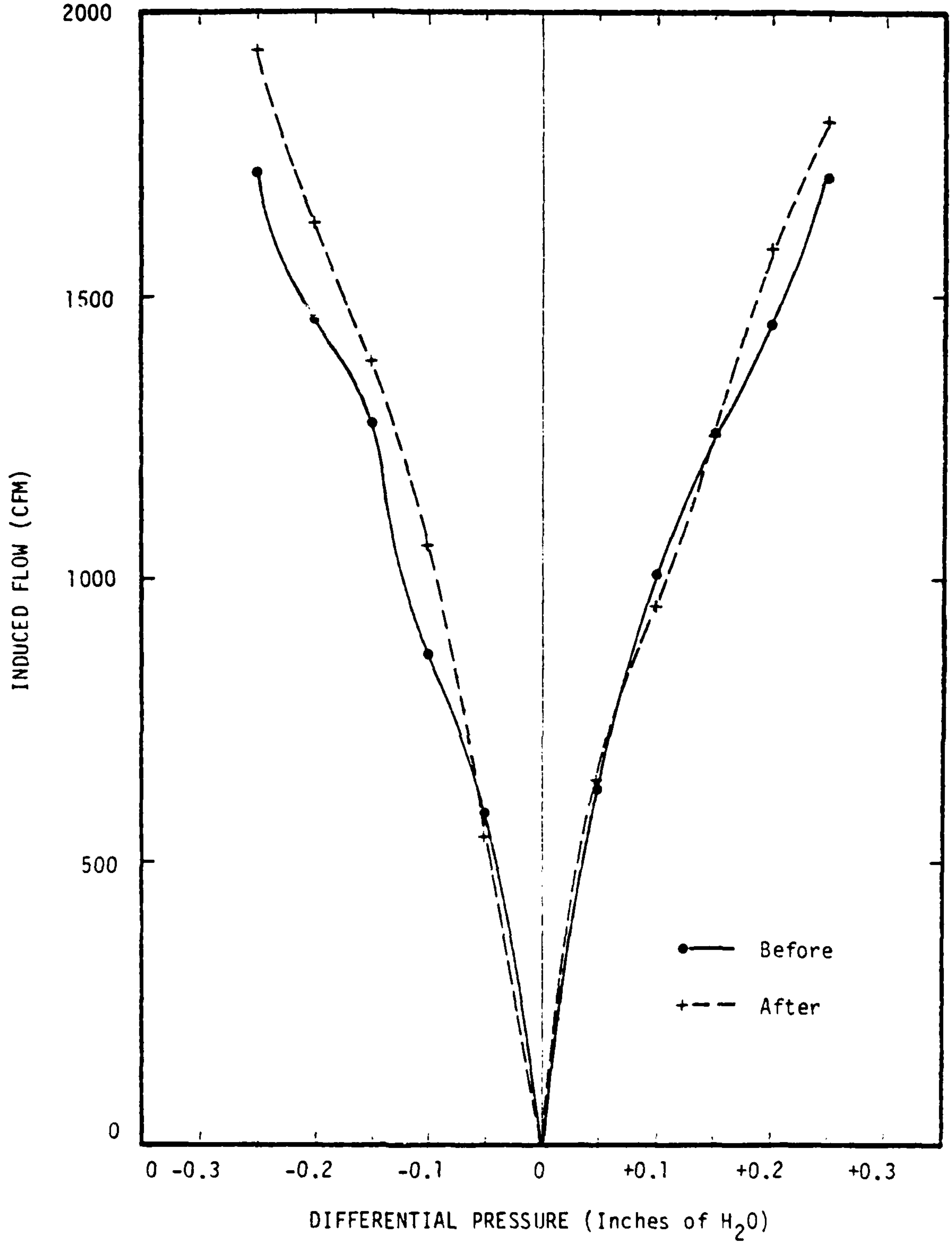

Figure A.14 Induced Flow versus Pressure for Apartment No. 8149.

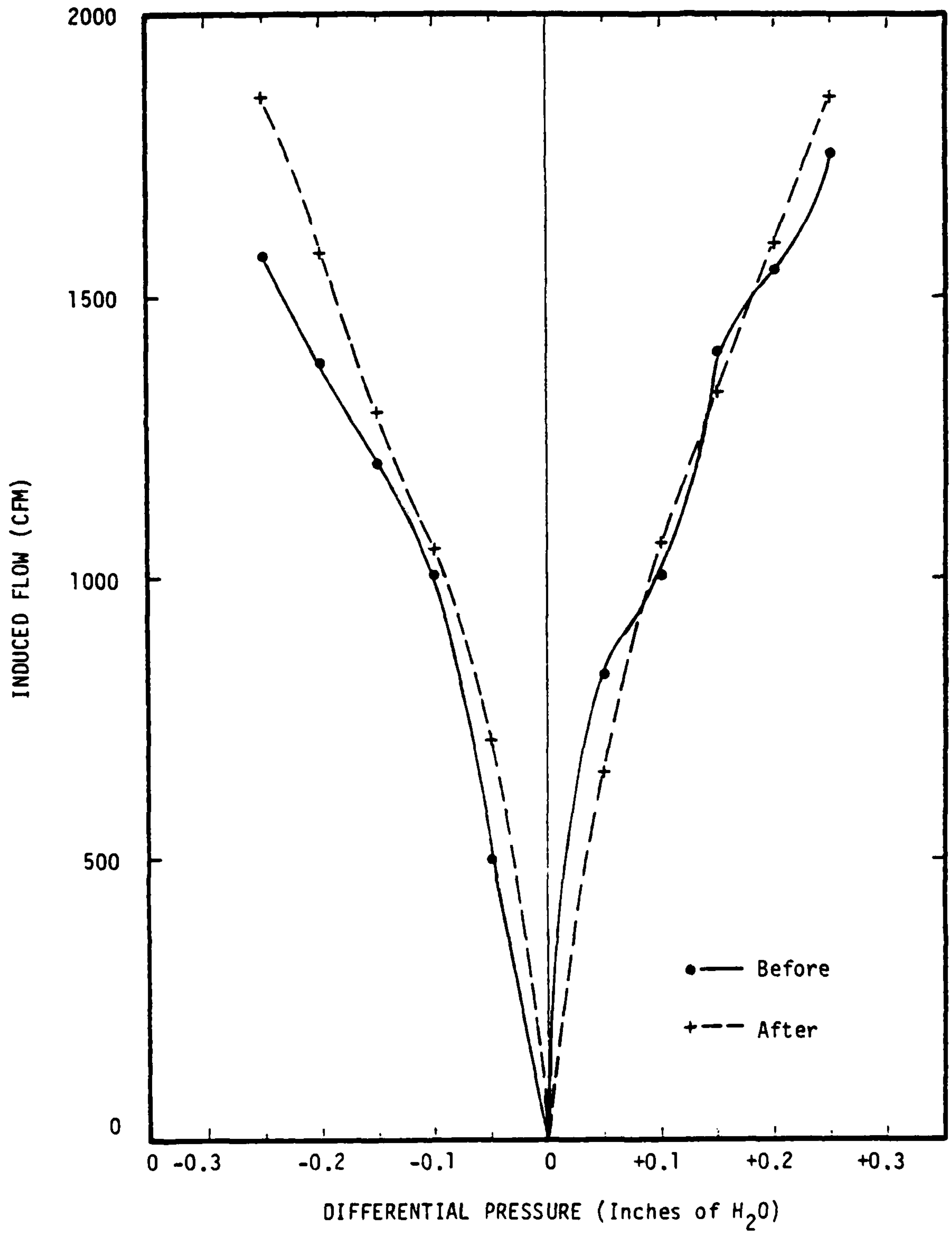

Figure A.15 Induced Flow *versus* Pressure for Apartment No. 8150.

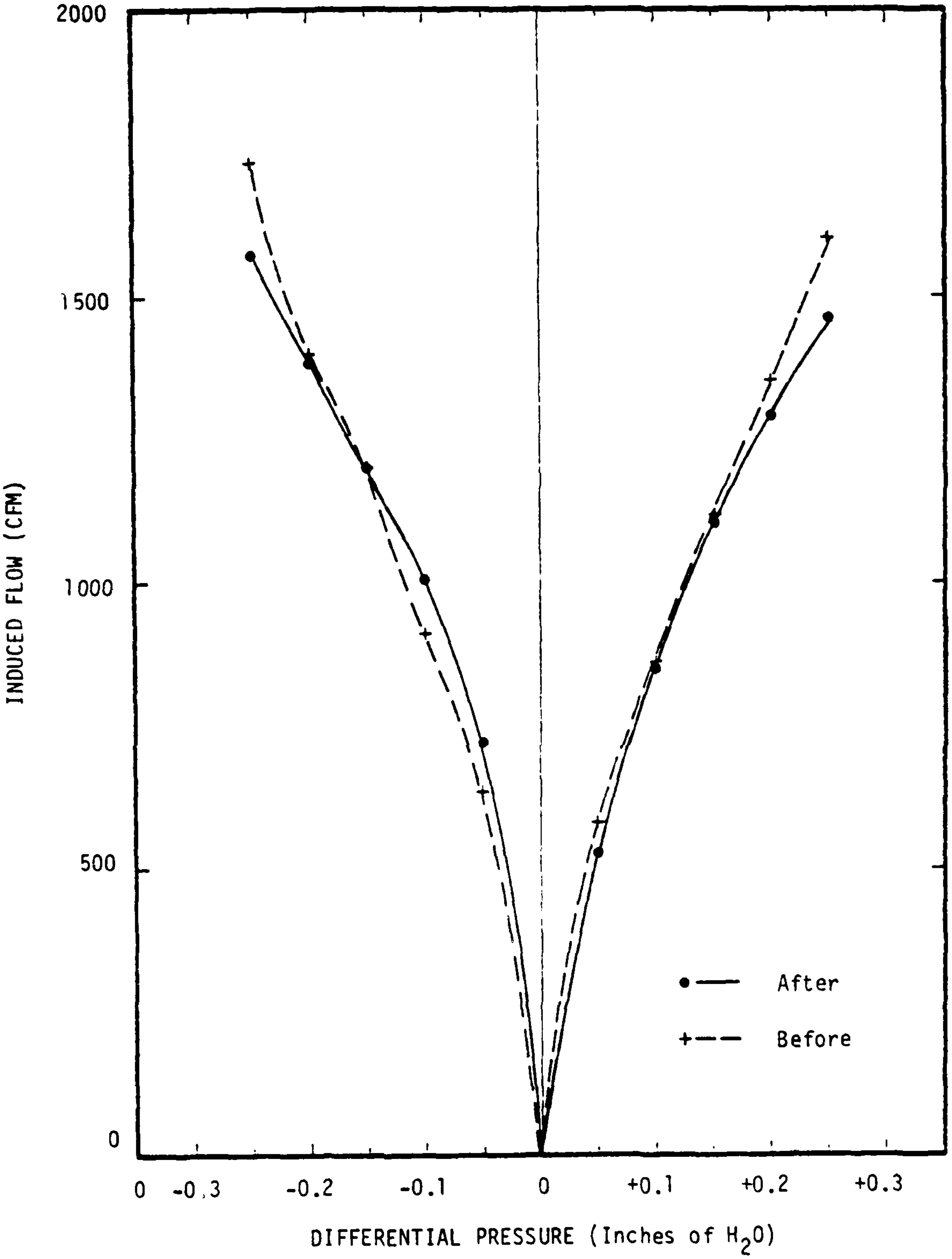

Figure A.16 Induced Flow versus Pressure for Apartment No. 8151.

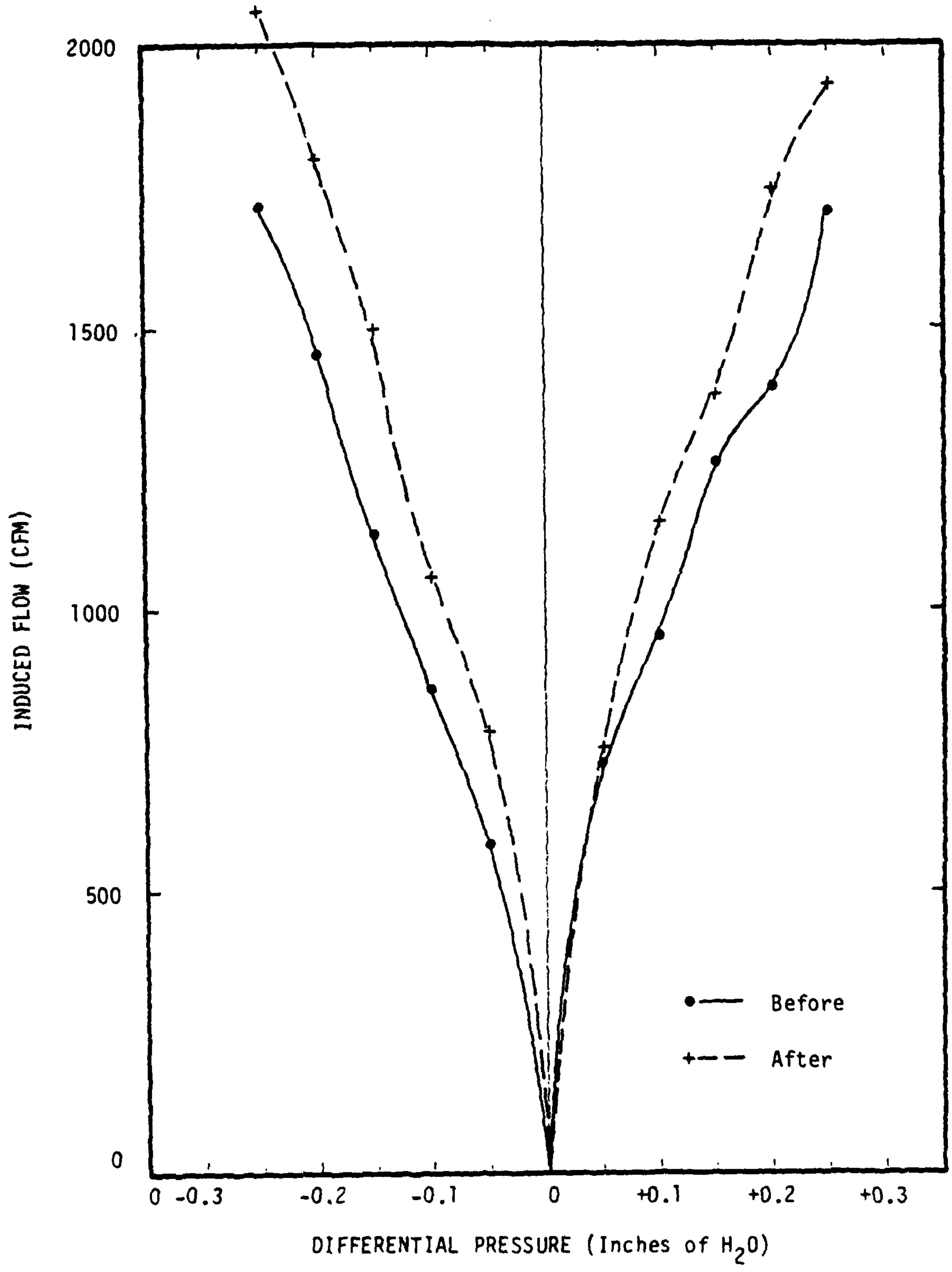

Figure A.17 Induced Flow <u>versus</u> Pressure for Apartment No. 8152.

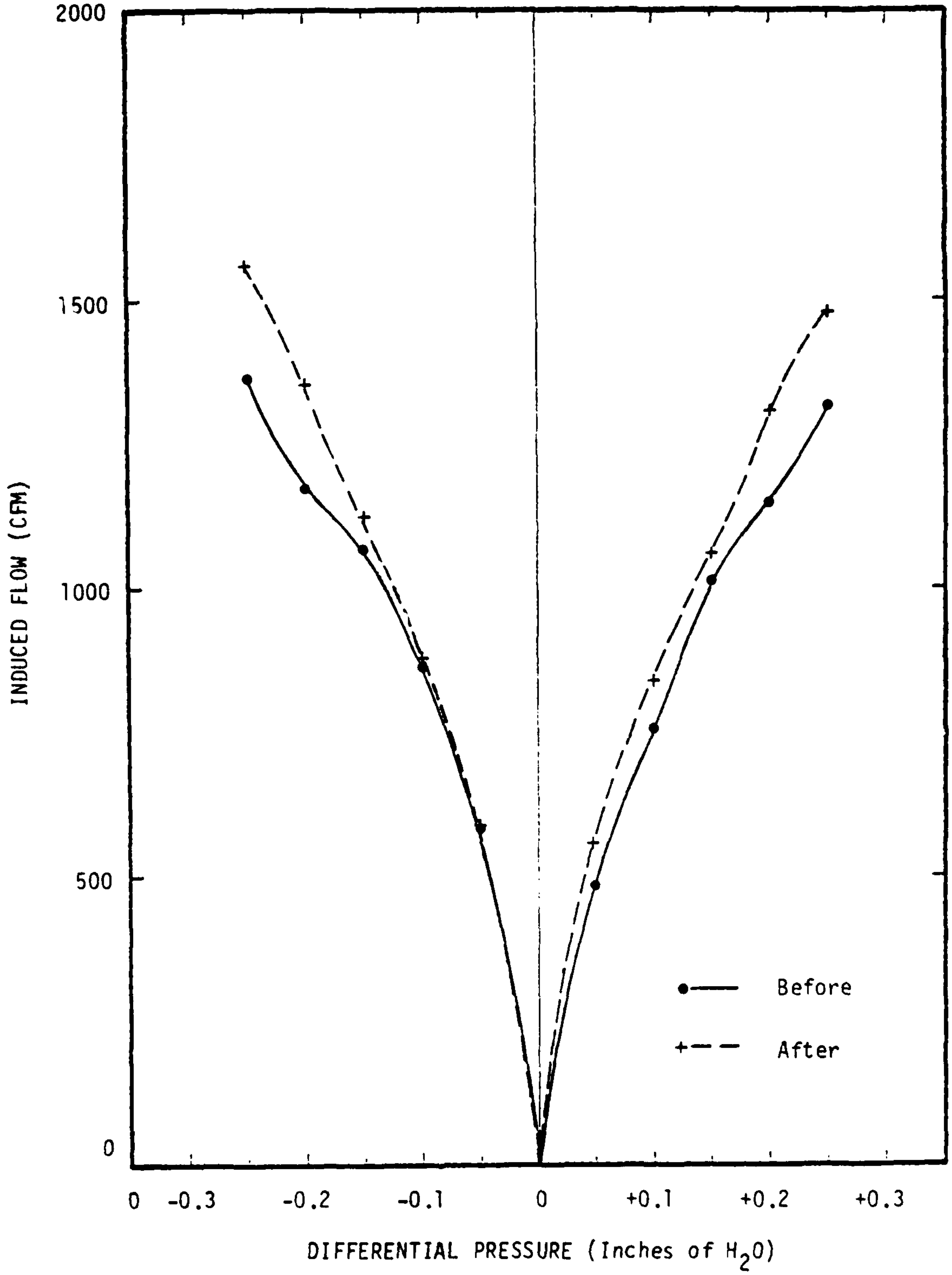

Figure A.18 Induced Flow versus Pressure for Apartment No. 8153.

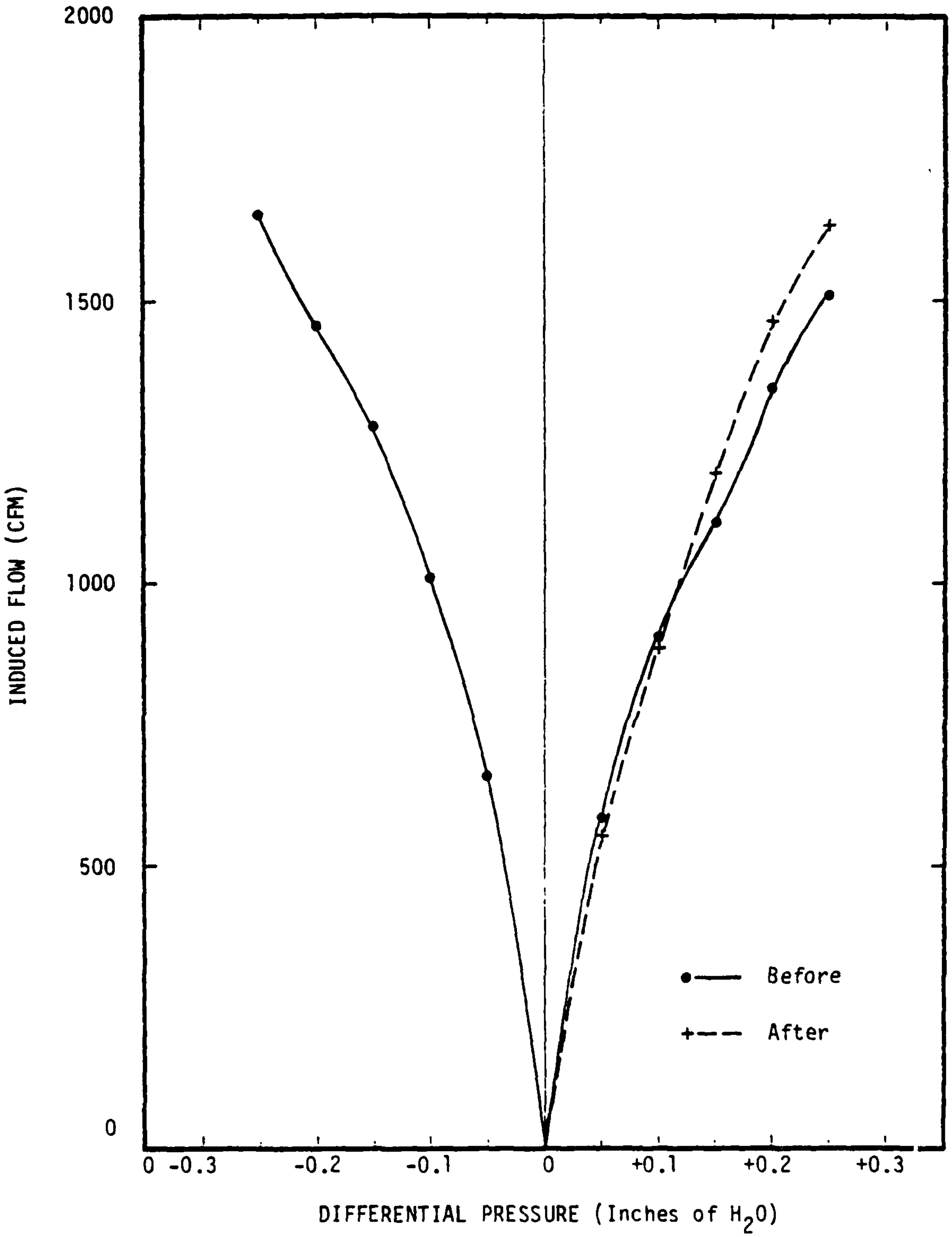

Figure A.19 Induced Flow versus Pressure for Apartment No. 8160.

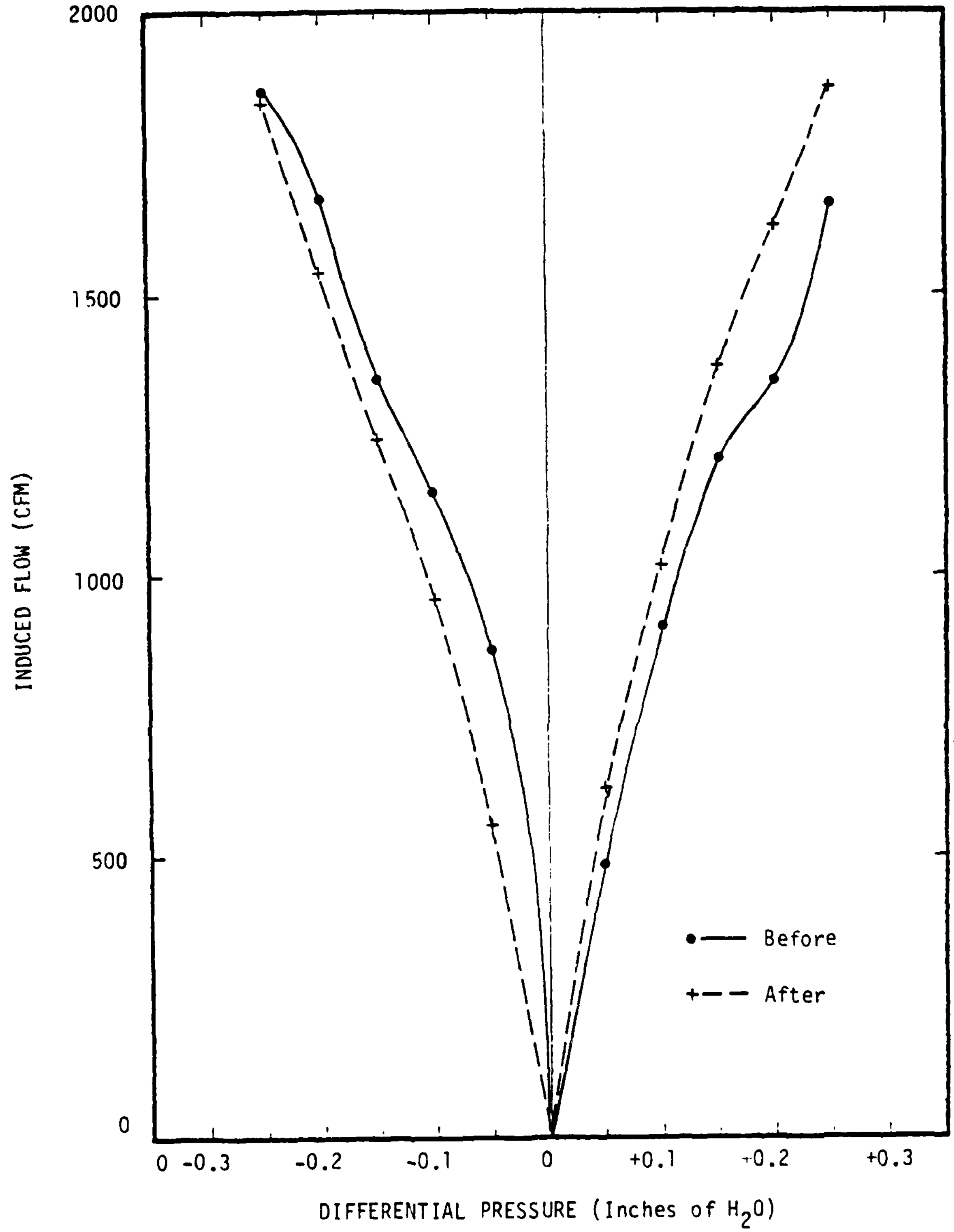

Figure A.20 Induced Flow <u>versus</u> Pressure for Apartment No. 8161.

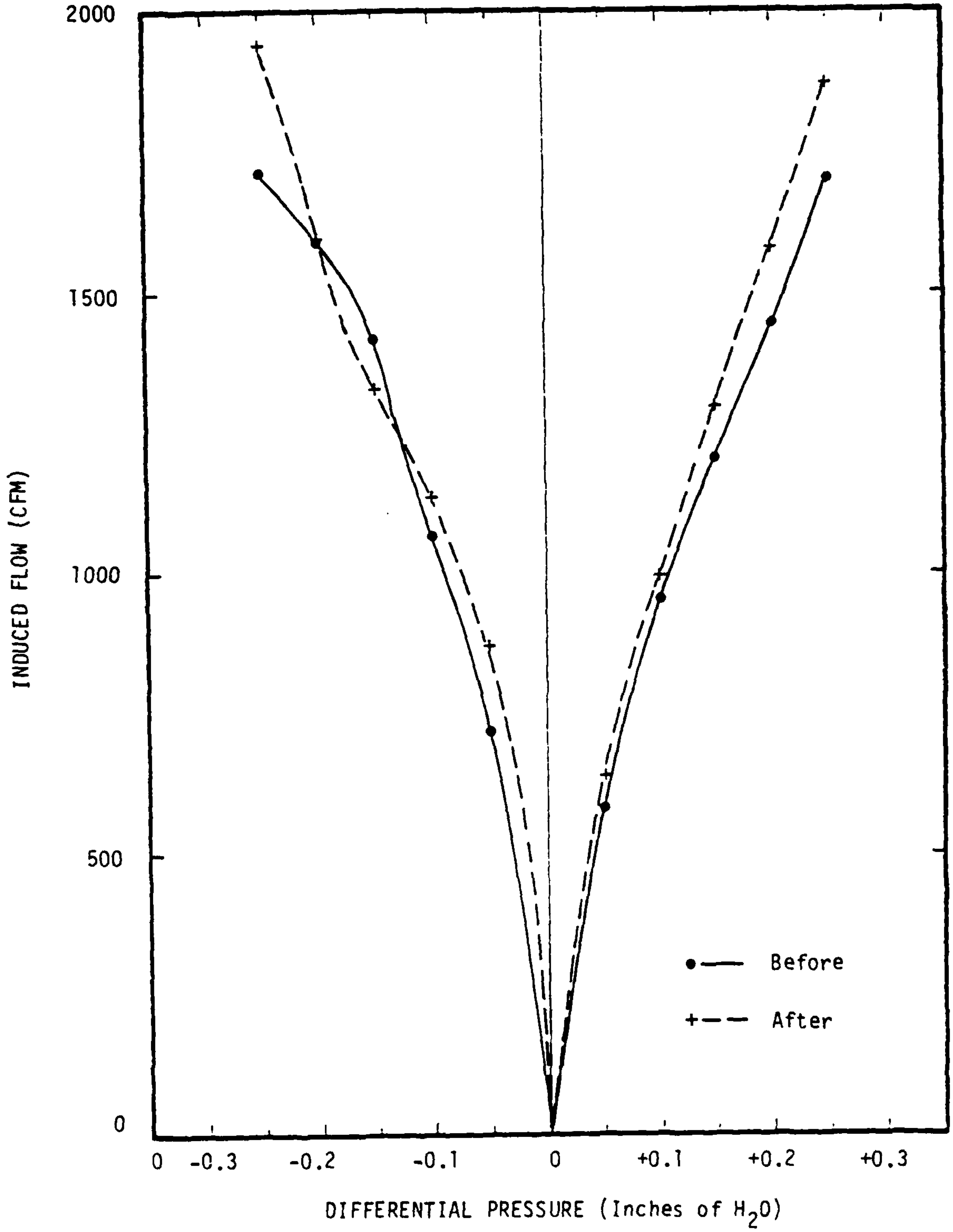

Figure A.21 Induced Flow versus Pressure for Apartment No. 8162.

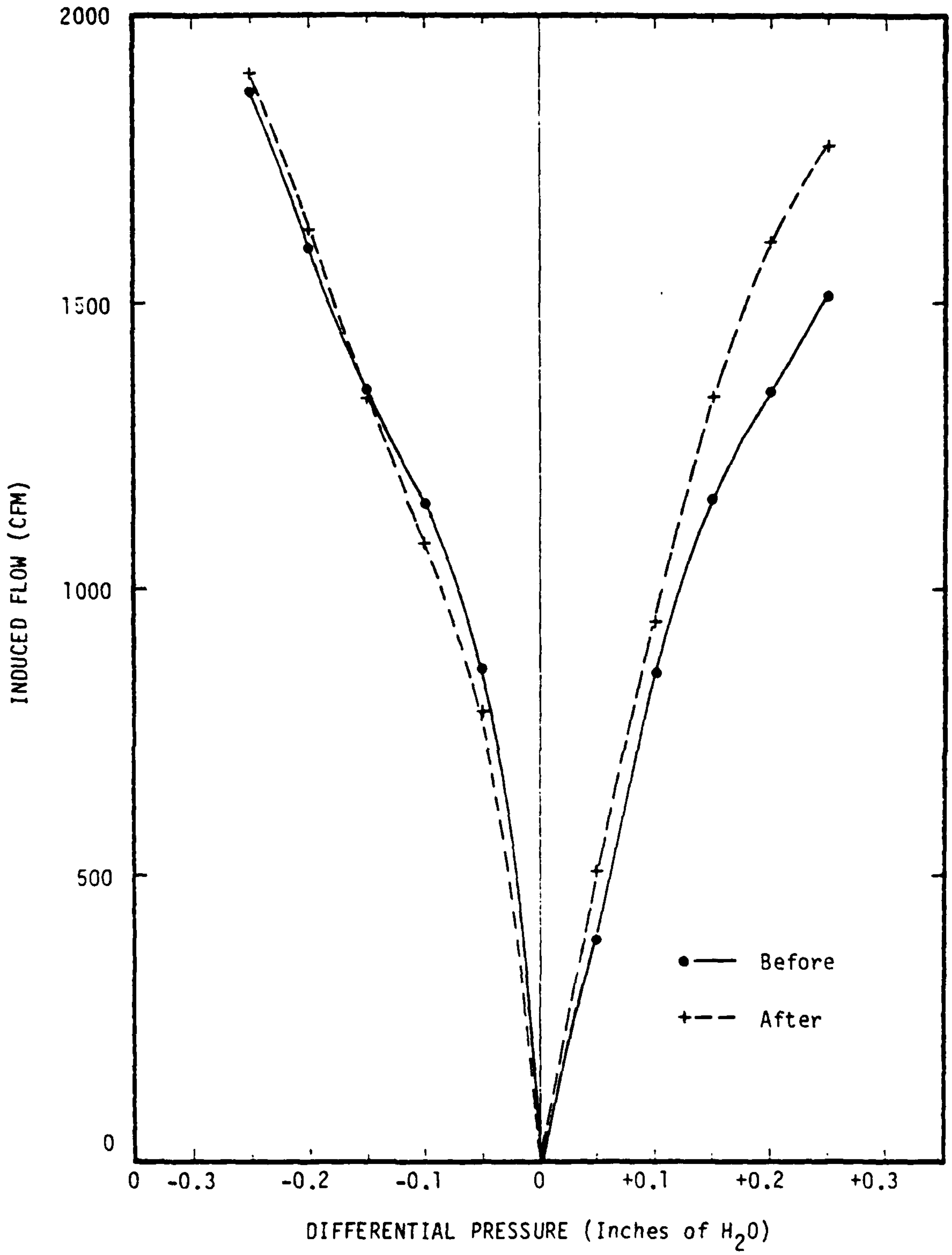

Figure A.22 Induced Flow versus Pressure for Apartment No. 8163.

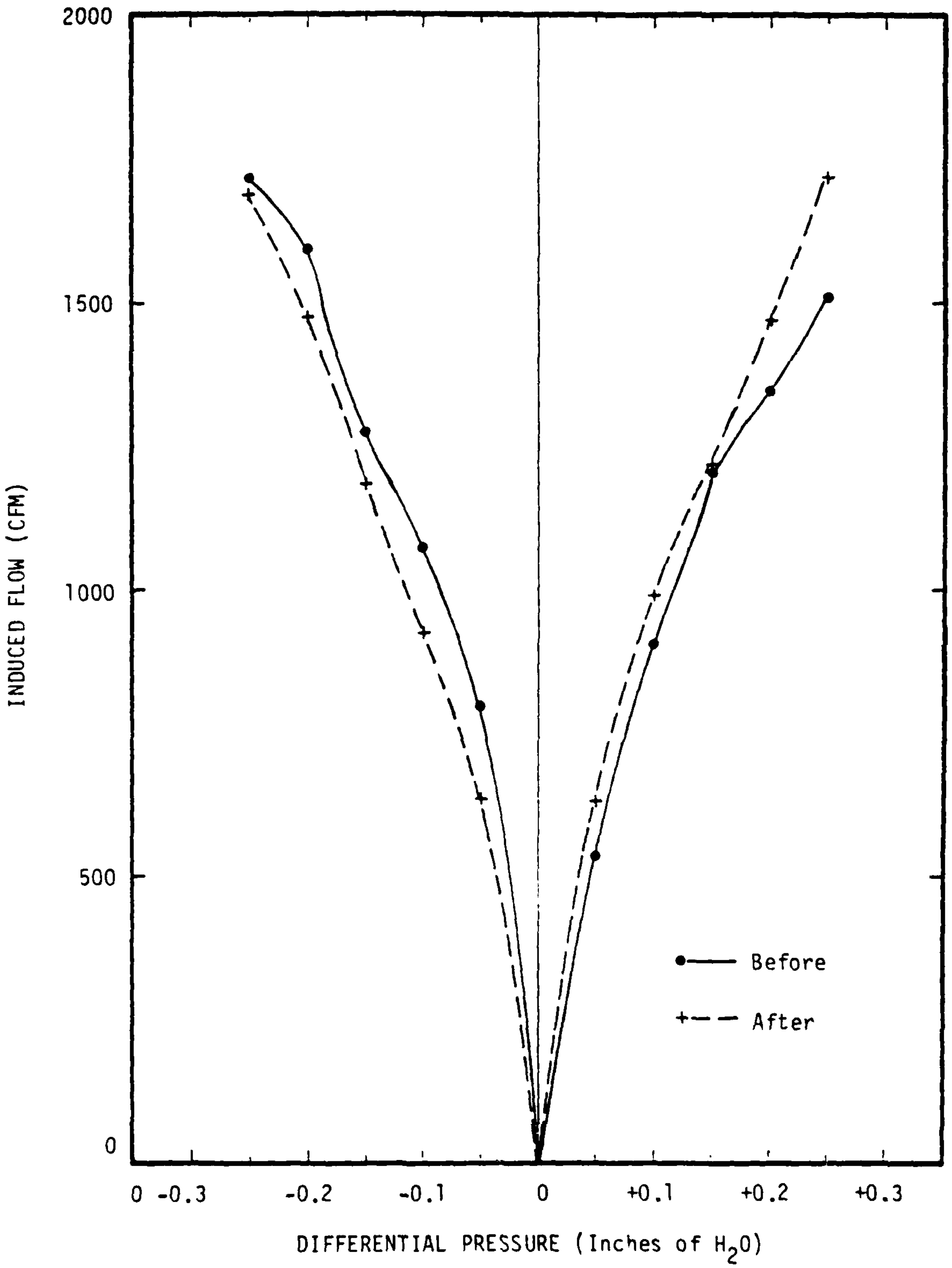

Figure A.23 Induced Flow versus Pressure for Apartment No. 8164.

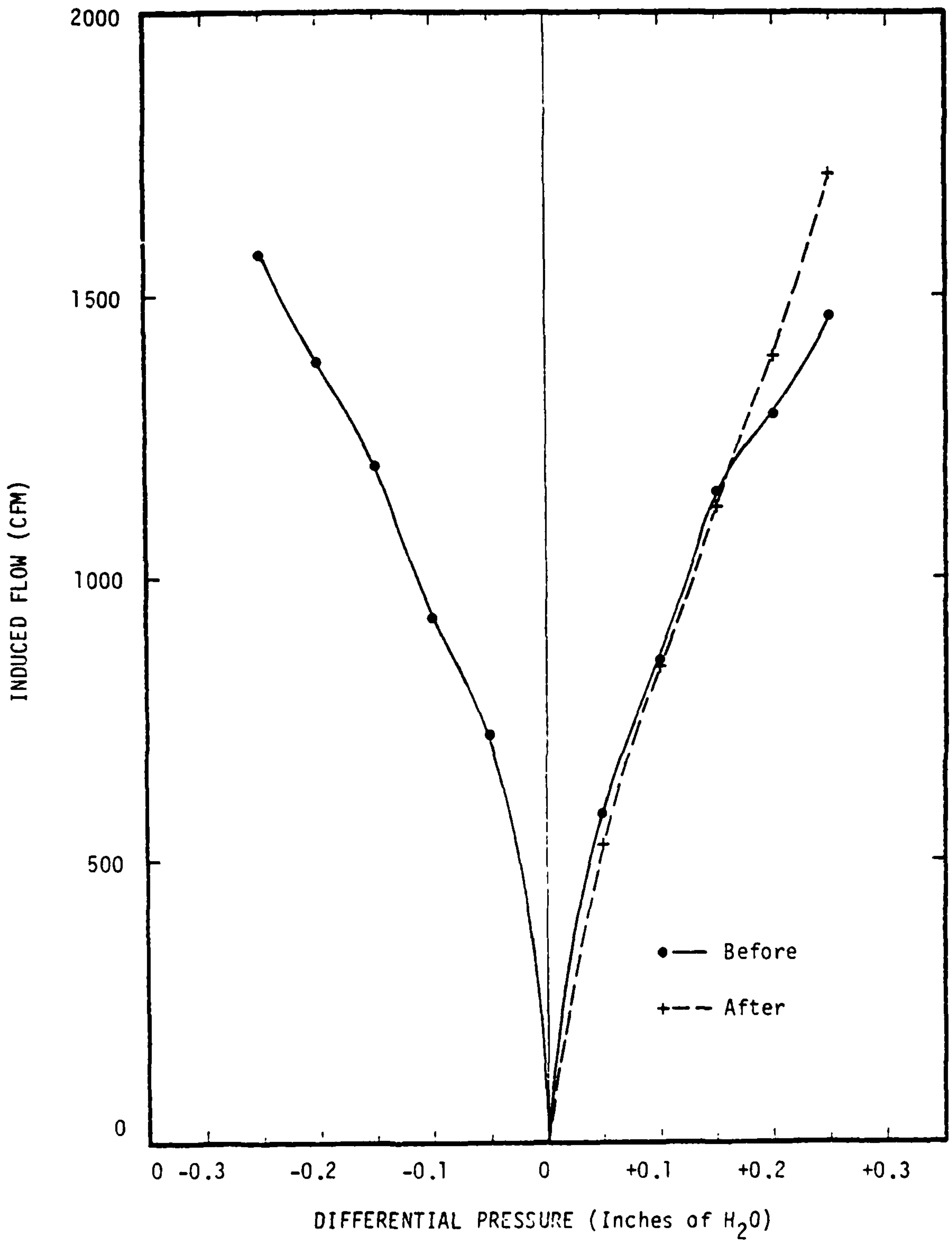

Figure A.24 Induced Flow *versus* Pressure for Apartment No. 8165.

APPENDIX B

ON-SITE METEOROLOGICAL AND TRACER CONCENTRATION DECAY DATA

In this Appendix we present on-site meteorological data (Appendix B.1) and actual concentration decay data (Appendix B.2). Meteorological conditions were monitored using a Meteorology Research Incorporated portable meteorological monitoring station, located in a clearing 200 yeards North of the housing office at Willoughby Bay.

All concentration decay measurements were performed using a Systems, Science and Software Model 215AUP Envirometer. The line on each decay curve represents a straight line fit to the data from which an air infiltration rate can be calculated.

APPENDIX B.1

ON-SITE METEOROLOGICAL DATA

LIST OF TABLES - APPENDIX B.1

TABLE B-I

ON-SITE METEOROLOGICAL DATA FOR 11/27/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0900	270°	7.5	52
0930	285°	7.5	52
1000	285°	7.5	53
1030	285°	6.	57
1100	285°	6.	58
1130	270°	5.	59
1200	270°	5.	60
1230	285°	4.5	61
1300	300°	4.	61
1330	300°	2.5	61
1400	300°	2.5	61
1430	315°	2.5	62
1500	270°	2.	64
1530	195°	2.	65
1600	90°	2.5	63
1630	100°	3.	57
1700	120°	3.	55
1730	135°	3.	53
1800	165°	3.	53
1830	180°	3.	53
1900	180°	3.	53
1930	180°	3.5	53
2000	180°	3.75	53

TABLE B-II

ON-SITE METEOROLOGICAL DATA FOR 11/28/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	210°	8.	51
0830			53
0900			55
0930			58
1000			60
1030			62
1100			65
1130			65
1200	235°	10.	67
1230	235°	9.5	67
1300	225°	9.5	67
1330	225°	9.5	67
1400	220°	9.	67
1430	220°	10.	67
1500	220°	9.5	66
1530	220°	9.5	65
1600	220°	5.	64
1630	210°	5.	62
1700	235°	4.5	61
1730	240°	3.75	59
1800	240°	3.75	58
1830	240°	3.75	58
1900	240°	4.	57
1930	240°	7.	55
2000	240°	7.5	55

TABLE B-III

ON-SITE METEOROLOGICAL DATA FOR 11/29/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	330°	5.	39
0830	330°	9.5	39
0900	330°	9.	39
0930	330°	8.5	40
1000	330°	5.	40
1030	0	5.	41
1100	0	5.	40
1130	330°	5.	41
1200	250°	3.	42
1230	285°	5.	43
1300	285°	5.5	42
1330	285°	6.	41
1400	270°	7.5	43
1430	285°	7.5	42
1500	300°	9.5	41
1530	285°	9.5	41
1600	285°	10.	41
1630	285°	15.	41
1700	285°	15.	41
1730	285°	15.	40
1800	285°	15.	39
1830	285°	15.	39
1900	285°	15.	38
1930	285°	15.	38
2000	285°	15.	37

TABLE B-IV

ON-SITE METEOROLOGICAL DATA FOR 11/30/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	270°	5.	27
0830	270°	5.	27
0900	285°	5.	28
0930	285°	7.5	28
1000	300°	7.	30
1030	300°	7.	31
1100	285°	6.	32
1130	285°	6.	33
1200	270°	6.5	33
1230	255°	6.	33
1300	270°	6.	35
1330	240°	6.	36
1400	280°	7.	36
1430	270°	7.5	37
1500	255°	7.5	38
1530	210°	7.5	38
1600	240°	7.5	38
1630	250°	7.5	37
1700	250°	7.5	37
1730	225°	7.5	36
1800	225°	7.5	35
1900	210°	7.	35
1930	210°	7.	34
2000	210°	6.	33

TABLE B-V

ON-SITE METEOROLOGICAL DATA FOR 12/1/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	200°	2.	30
0830	200°	5.	33
0900	200°	5.	35
0930	210°	6.	37
1000	200°	6.	38
1030	210°	6.	39
1100	210°	6.5	39
1130	210°	6.5	40
1200	210°	6.5	41
1230	210°	6.5	42
1300	210°	6.5	43
1330	210°	5.	44
1400	210°	5.	44
1430	210°	5.	45
1500	210°	5.	47
1530	210°	6.	47
1600	210°	6.	45
1630	210°	6.	43
1700	200°	5.	42
1730	210°	3.	40
1800	200°	3.	39
1830	200°	3.	38
1900	200°	3.	38
1930	210°	3.75	38
2000	210°	5.	38

TABLE B-VI

ON-SITE METEOROLOGICAL DATA FOR 12/2/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	330°	12.5	35
0830	330°	12.5	35
0900	330°	14.5	35
0930	330°	15.	35
1000	330°	15.	35
1030	330°	15.	35
1100	330°	15.	36
1130	330°	15.	37
1200	330°	15.	37
1230	330°	14.5	37
1300	330°	14.0	37
1330	330°	14.5	38
1400	330°	15.	37
1430	330°	15.	37
1500	330°	15.	38
1530	330°	14.5	37
1600	330°	14.	37
1630	330°	14.	36
1700	330°	14.	36
1730	330°	14.	35
1800	330°	14.5	35
1830	330°	15.	35
1900	330°	15.	34
1930	330°	15.	34
2000	330°	15.	33

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TABLE B-VII

ON-SITE METEOROLOGICAL DATA FOR 12/3/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	340°	9.	28
0830	340°	9.	29
0900	340°	9.	29
0930	350°	9.	31
1000	330°	7.5	31
1030	330°	7.5	32
1100	330°	7.5	32
1130	360°	5.	34
1200	360°	5.	35
1230	360°	5.	35
1300	360°	4.5	35
1330	360°	3.	32
1400	270°	3.	35
1430	285°	3.	36
1500	315°	3.	36
1530	270°	3.	36
1600	250°	3.	36
1630	225°	5.	35
1700	240°	4.	33
1700	240°	4.	33
1730	240°	4.	33
1800	210°	4.	32
1830	160°	3.	29
1900	180°	2.5	28
1930	180°	2.5	28
2000	180°	4.	28

TABLE B-VIII

ON-SITE METEOROLOGICAL DATA FOR 12/4/79

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0800	225°	9.	31
0830	240°	9.	32
0900	240°	9.	32
0930	240°	9.	32
1000	225°	9.5	34
1030	240°	9.5	37
1100	255°	10.	39
1130	270°	10.	41
1200	280°	9.	42
1230	285°	9.	43
1300	285°	8.	45
1330	285°	8.	46
1400	300°	7.5	47
1430	300°	5.	48
1500	270°	5.	48
1530		DISMANTLED MET STATION	

TABLE B-IX

ON-SITE METEOROLOGICAL DATA FOR 10/15/80

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0830	210°	2.5	49
0845	210°	3.	52
0900	210°	3.	53
0915	210°	5.	55
0930	210°	5.	56
0945	210°	5.	58
1000	210°	5.	59
1015	210°	5.	60
1030	230°	5.5	61
1045	230°	5.5	62
1100	230°	5.5	64
1115	210°	5.5	65
1130	220°	5.5	66
1145	220°	6.	67
1200	220°	7.	67
1215	220°	7.	67
1230	210°	6.	69
1245	210°	5.5	70
1300	210°	5.5	70
1315	210°	5.5	70
1330	210°	5.5	71
1345	210°	5.5	73
1400	240°	5.5	73
1415	240°	5.5	73
1430	210°	5.5	73
1445	240°	6.	73
1500	240°	7.	73
1515	240°	7.	73
1530	240°	8.	73
1545	240°	8.	72

TABLE B-X

ON-SITE METEOROLOGICAL DATA FOR 10/16/80

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0830	210°	3.	55
0845	210°	4.	57
0900	210°	5.	59
0915	225°	5.	60
0930	225°	5.	62
0945	210°	5.	63
1000	225°	5.	64
1015	225°	5.	65
1030	225°	5.	65
1045	225°	5.	66
1100	225°	5.	67
1115	225°	5.	68
1130	225°	6.	68
1145	270°	7.	70
1200	270°	7.	70
1215	270°	7.	70
1230	270°	6.	71
1245	225°	6.	72
1300	225°	6.	72
1315	270°	5.5	72
1330	270°	5.	72
1345	210°	5.	73
1400	210°	5.	74
1415	210°	5.	74
1430	210°	5.	74
1445	225°	5.	75
1500	210°	5.	75
1515	210°	5.	75
1530	210°	5.	75
1545	220°	5.	74

TABLE B-XI

ON-SITE METEOROLOGICAL DATA FOR 10/17/80

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0830	200°	1.	59
0845	210°	1.	61
0900	200°	1.	63
0915	200°	1.	65
0930	315°	1.	66
0945	300°	1.5	67
1000	315°	1.5	67
1015	315°	1.5	67
1030	310°	2.	67
1045	315°	2.	68
1100	315°	2.	69
1115	330°	2.5	71
1130	330°	2.5	71
1145	330°	2.5	72
1200	360°	2.5	72
1215	30°	2.5	71
1230	30	3.	69
1245	60	4.	70
1300	60	5.	68

TABLE B-XII

ON-SITE METEOROLOGICAL DATA FOR 10/18/80

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
1100	220°	6.	73
1115	210°	6.	74
1130	210°	7.	74
1145	210°	8.	74
1200	210°	9.	74
1215	210°	9.	75
1230	210°	10.	75
1245	210°	10.	75
1300	210°	10.	76
1315	210°	9.	77
1330	210°	9.	77
1345	210°	8.5	77
1400	210°	10.	76
1415	210°	9.5	76
1430	210°	9.	75
1445	210°	8.	76
1500	210°	8.	77
1515	210°	9.	77
1530	210°	10.	77
1545	210°	9.	77
1600	210°	9.	77
1615	210°	9.	77
1630	210°	9.	76
1645	210°	9.	74

TABLE B-XIII

ON-SITE METEOROLOGICAL DATA FOR 10/21/80

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0830	225°	5.	49
0900	225°	5.	52
0915	225°	5.	53
0930	225°	5.5	54
0945	240°	5.5	56
1000	240°	5.5	57
1015	225°	5.5	59
1030	225°	5.	60
1045	225°	5.	61
1100	225°	6.	62
1115	240°	6.	63
1130	240°	7.5	63
1145	240°	9.5	64
1200	240°	10.	64

TABLE B-XIV

ON-SITE METEOROLOGICAL DATA FOR 10/22/80

TIME	WIND DIRECTION	SPEED (mph)	TEMPERATURE (°F)
0900	215°	3.	56
0915	300°	3.	56
0930	300°	3.	57
0945	300°	2.5	58
1000	270°	2.5	58
1015	270°	2.5	58
1030	270°	2.5	59
1045	250°	2.5	60
1100	250°	2.5	61
1115	255°	2.5	62
1130	240°	2.5	63
1145	240°	2.5	66
1200	240°	2.5	68
1215	240°	2.5	69
1230	240°	2.5	70
1245	300°	2.5	70
1300	300°	2.5	68
1315	285°	2.5	68
1330	285°	2.	67
1345	360°	1.	68
1400	300°	1.	69
1415	315°	1.	68
1430	270°	1.	69
1445	330°	1.	68
1500	0°	1.	67
1515	60°	2.	64
1530	60°	2.5	63
1545	40°	2.5	63

APPENDIX B.2

TRACER CONCENTRATION DECAY CURVES

LIST OF FIGURES - APPENDIX B.2

LIST OF FIGURES - APPENDIX B.2
(Continued)

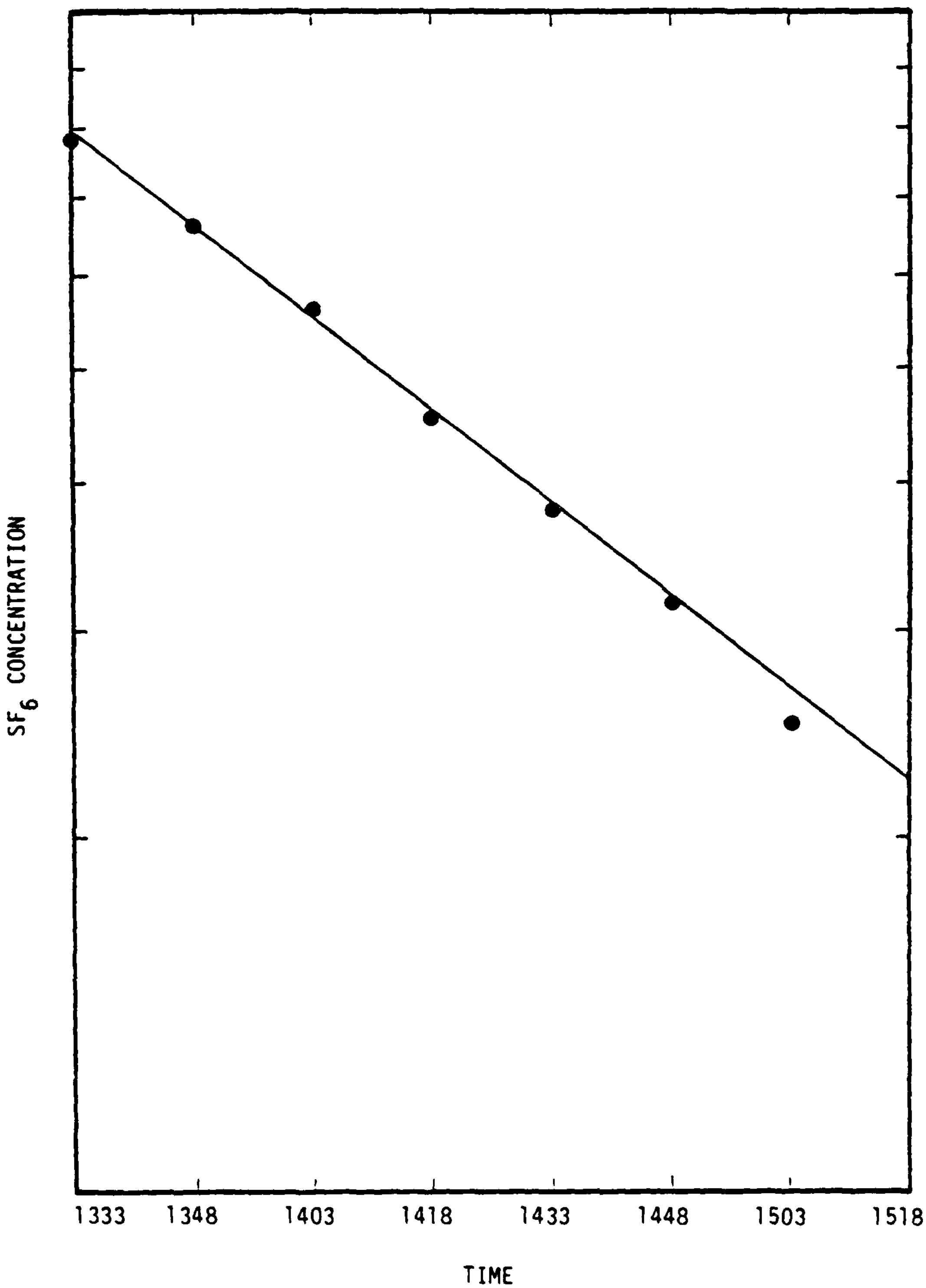

Figure B.1 Tracer Concentration Decay versus Time on 12/3/79 for Apartment No. 8123.

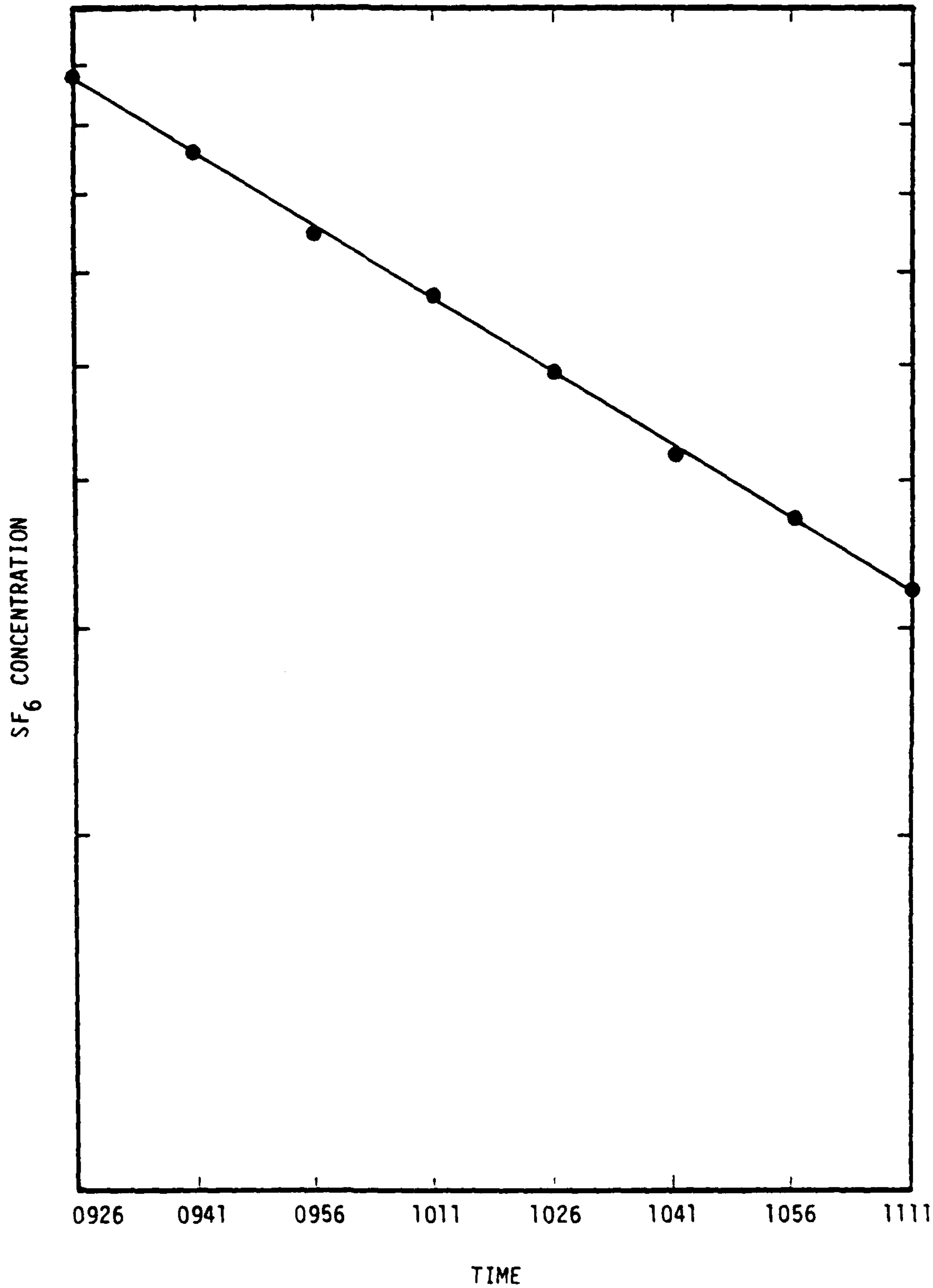

Figure B.2a Tracer Concentration Decay versus Time on 12/3/79 (A.M.) for Apartment No. 8130.

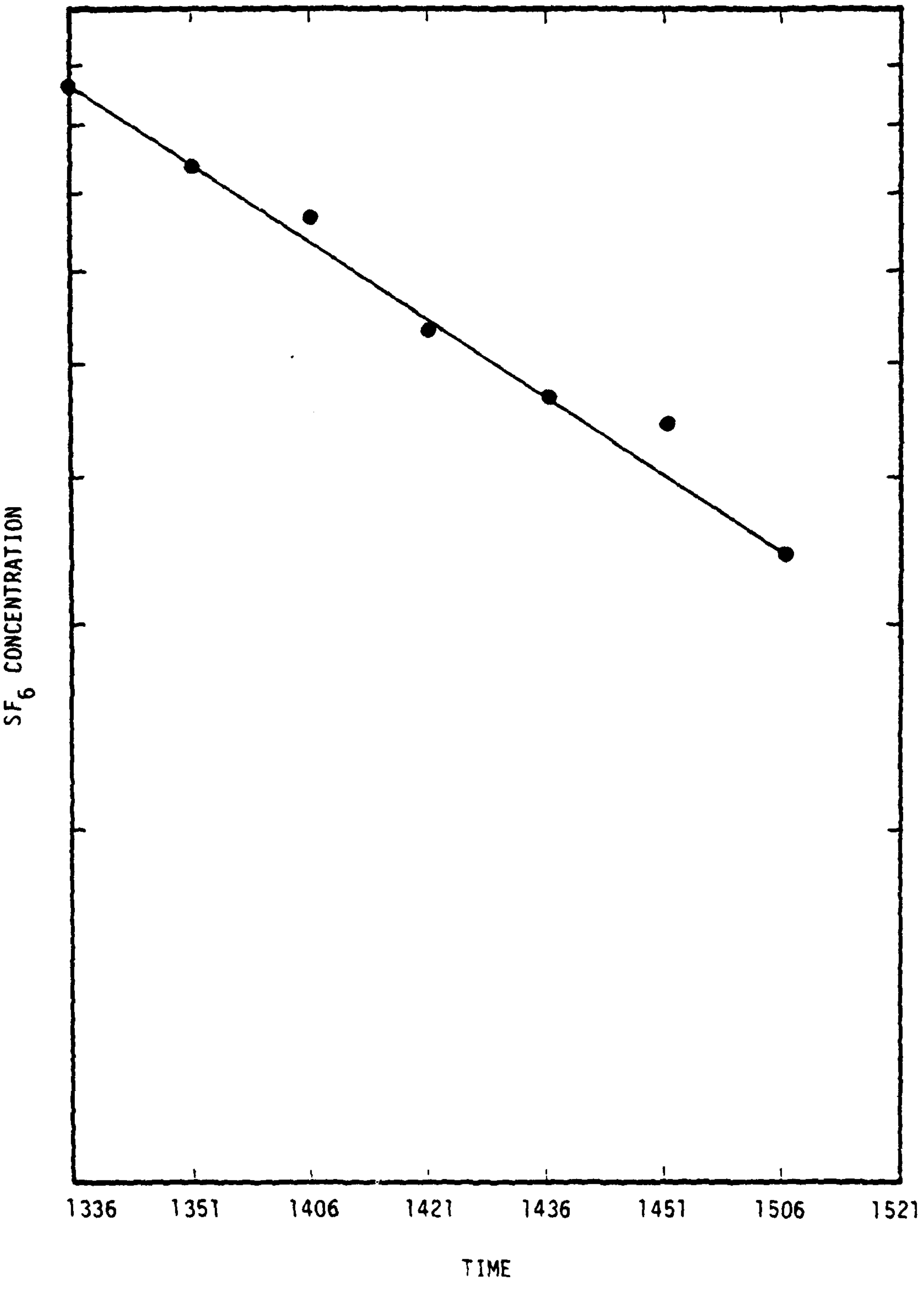

Figure B.2b Tracer Concentration Decay *versus* Time on 12/3/79 (P.M.) for Apartment No. 8130.

D-A128 562 AIR LEAKAGE MEASUREMENTS IN NAVY FAMILY HOUSING UNITS AT NORFOLK VIRGINIA(U) S-CUBED LA JOLLA CA P L LAGUS APR 83 SSS-R-82-5288-1 CEL-CR-83-018 N68305-79-C-0344

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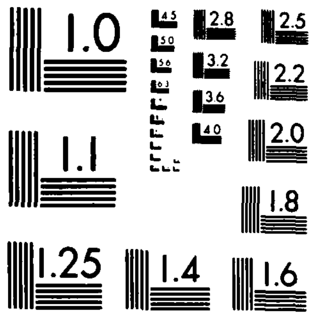

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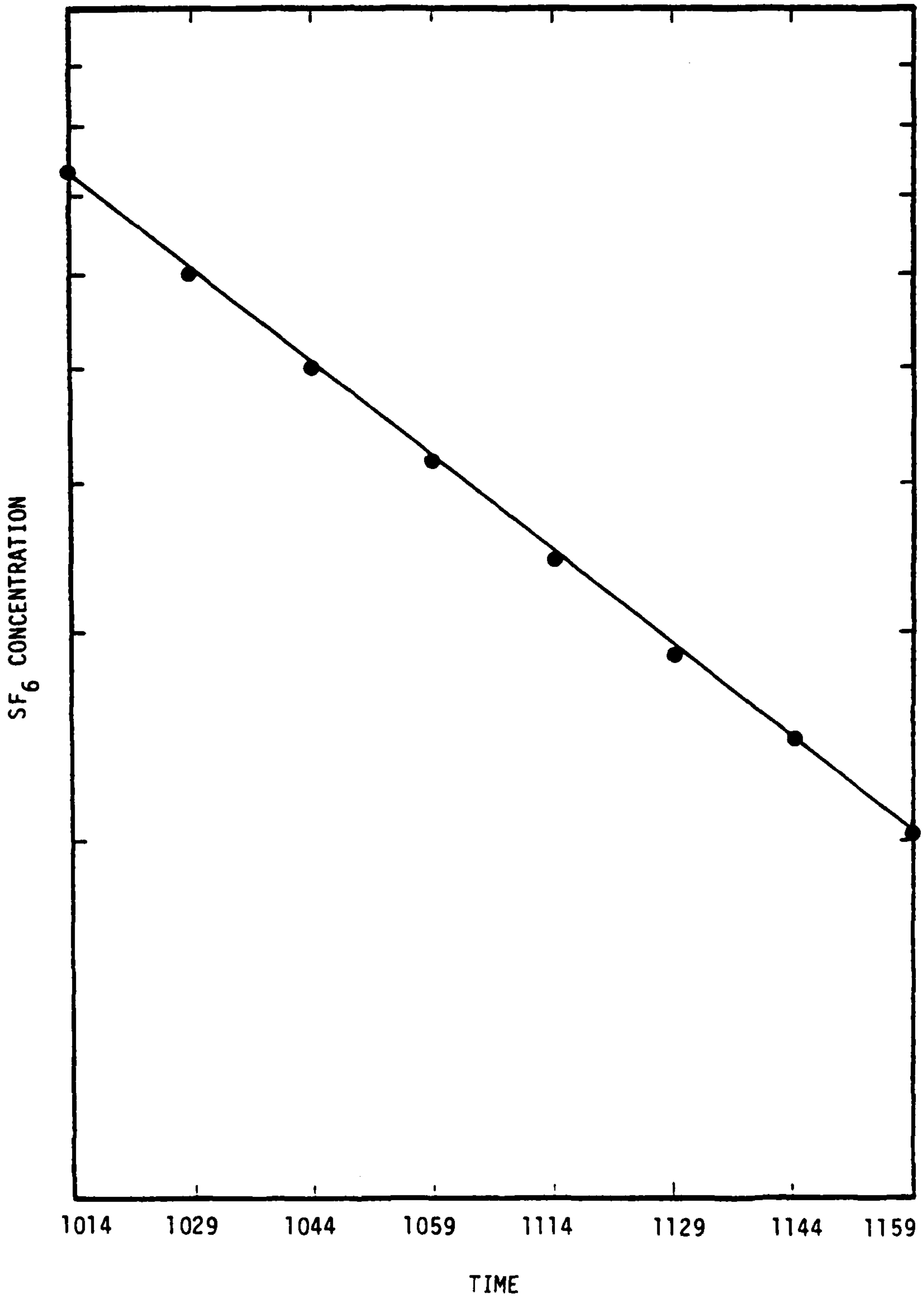

Figure B.3a Tracer Concentration Decay *versus* Time on 12/3/79 (A.M.) for Apartment No. 8148.

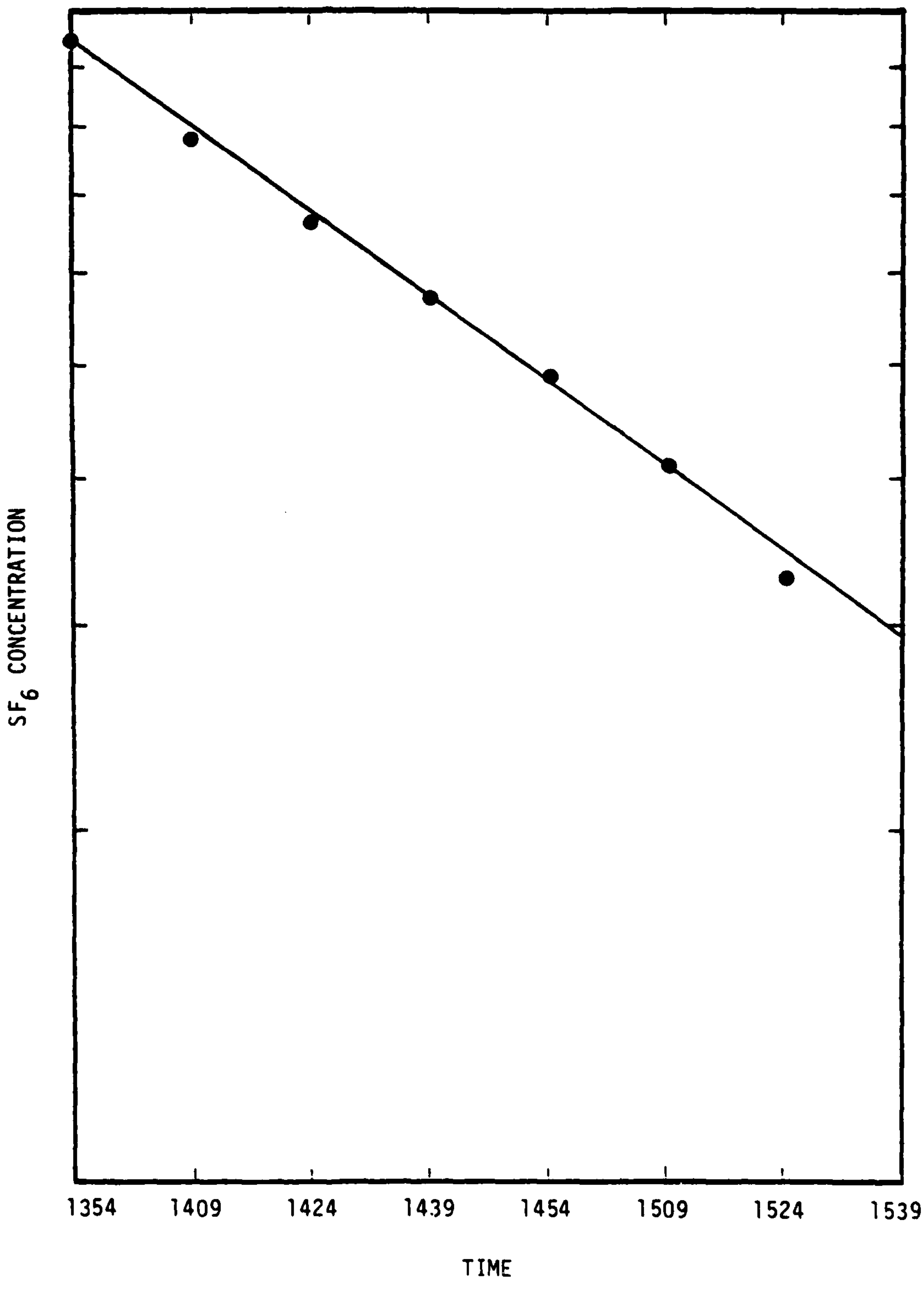

Figure B.3b Tracer Concentration Decay *versus* Time on 12/3/79 (P.M.) for Apartment No. 8148.

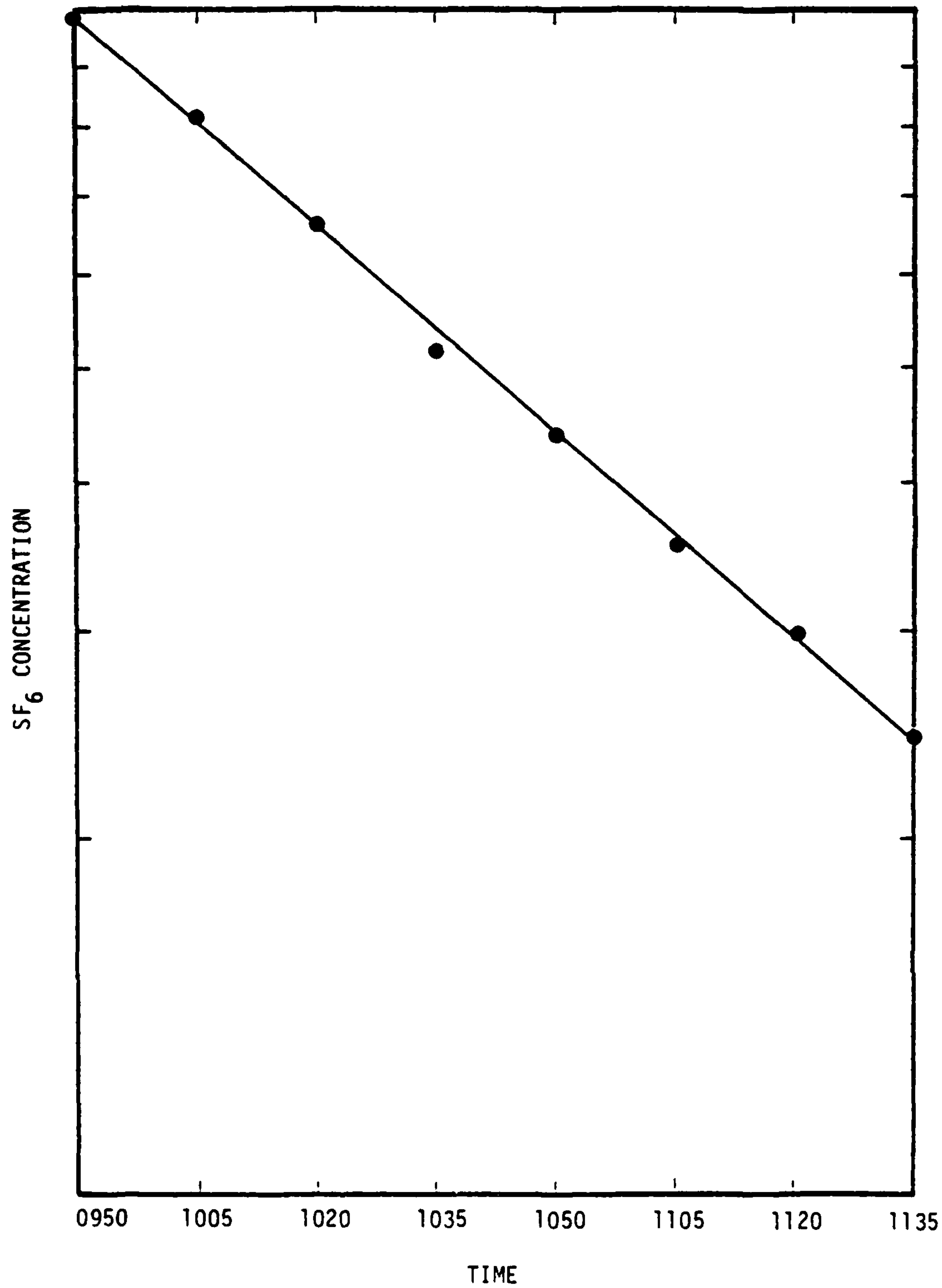

Figure B.4a Tracer Concentration Decay *versus* Time on 12/3/79 (A.M.) for Apartment No. 8165.

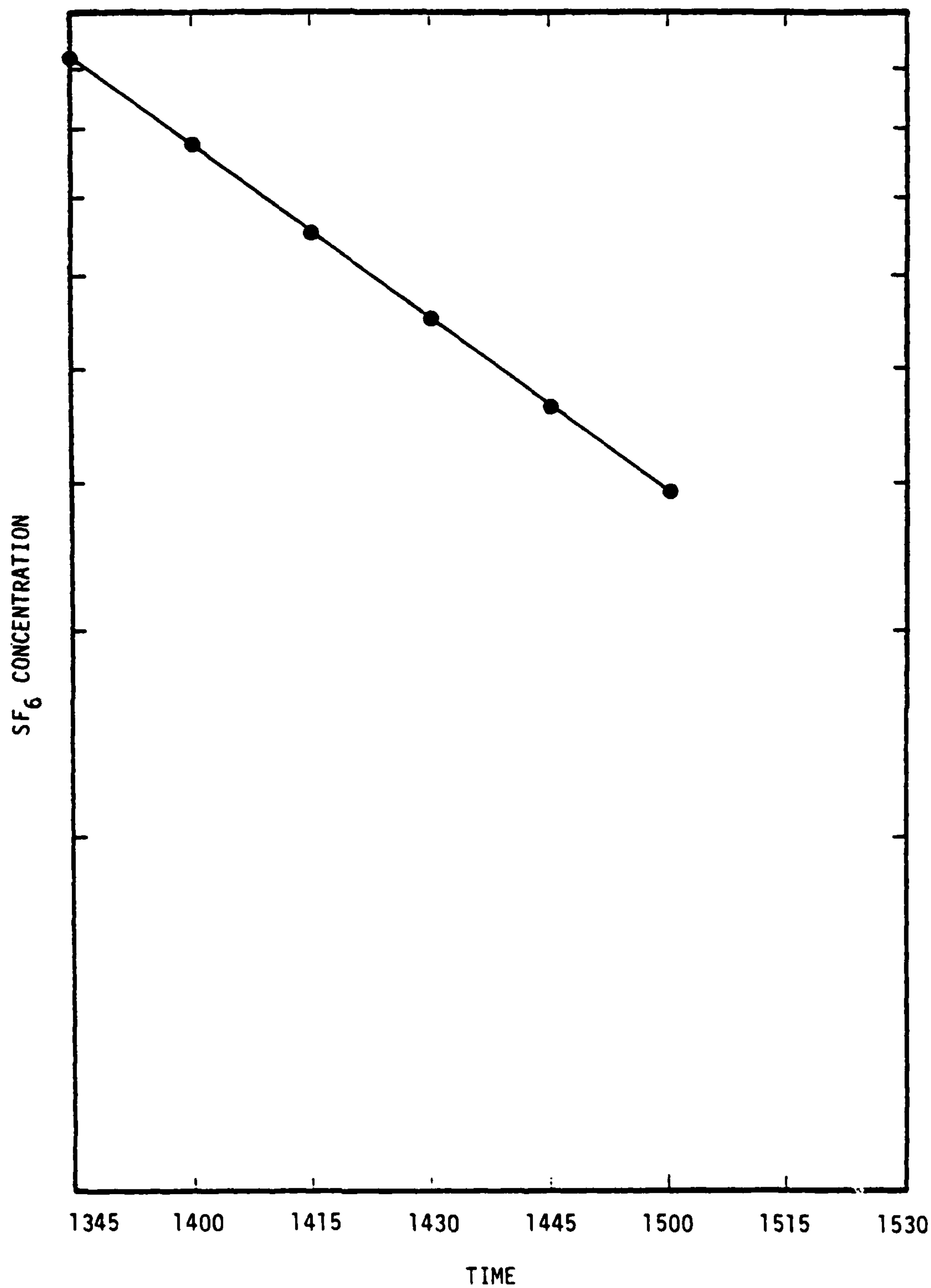

Figure B.4b Tracer Concentration Decay *versus* Time on 12/3/79 (P.M.) for Apartment No. 8165.

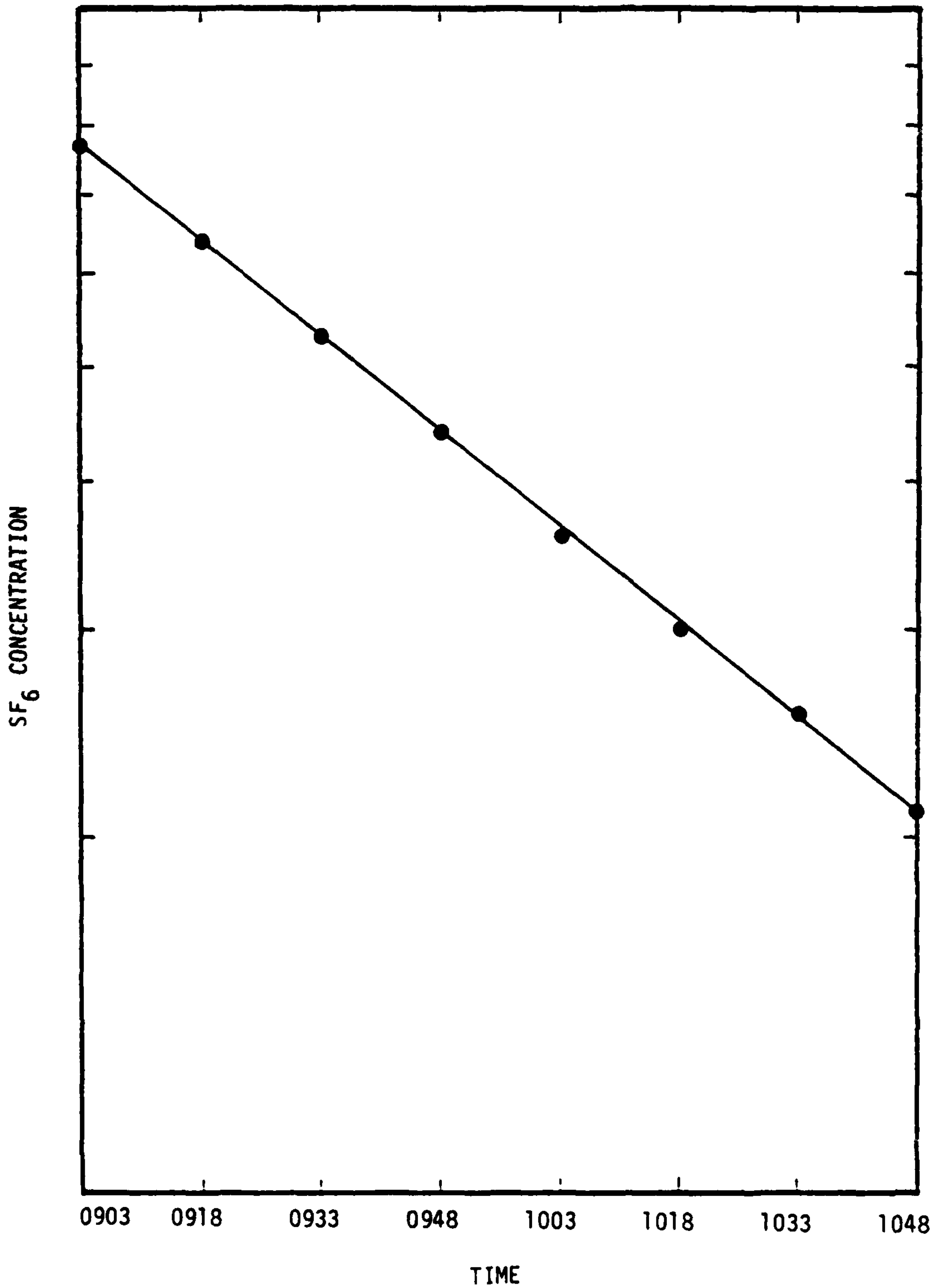

Figure B.5a Tracer Concentration Decay *versus* Time on 12/4/79 (A.M.) for Apartment No. 8121.

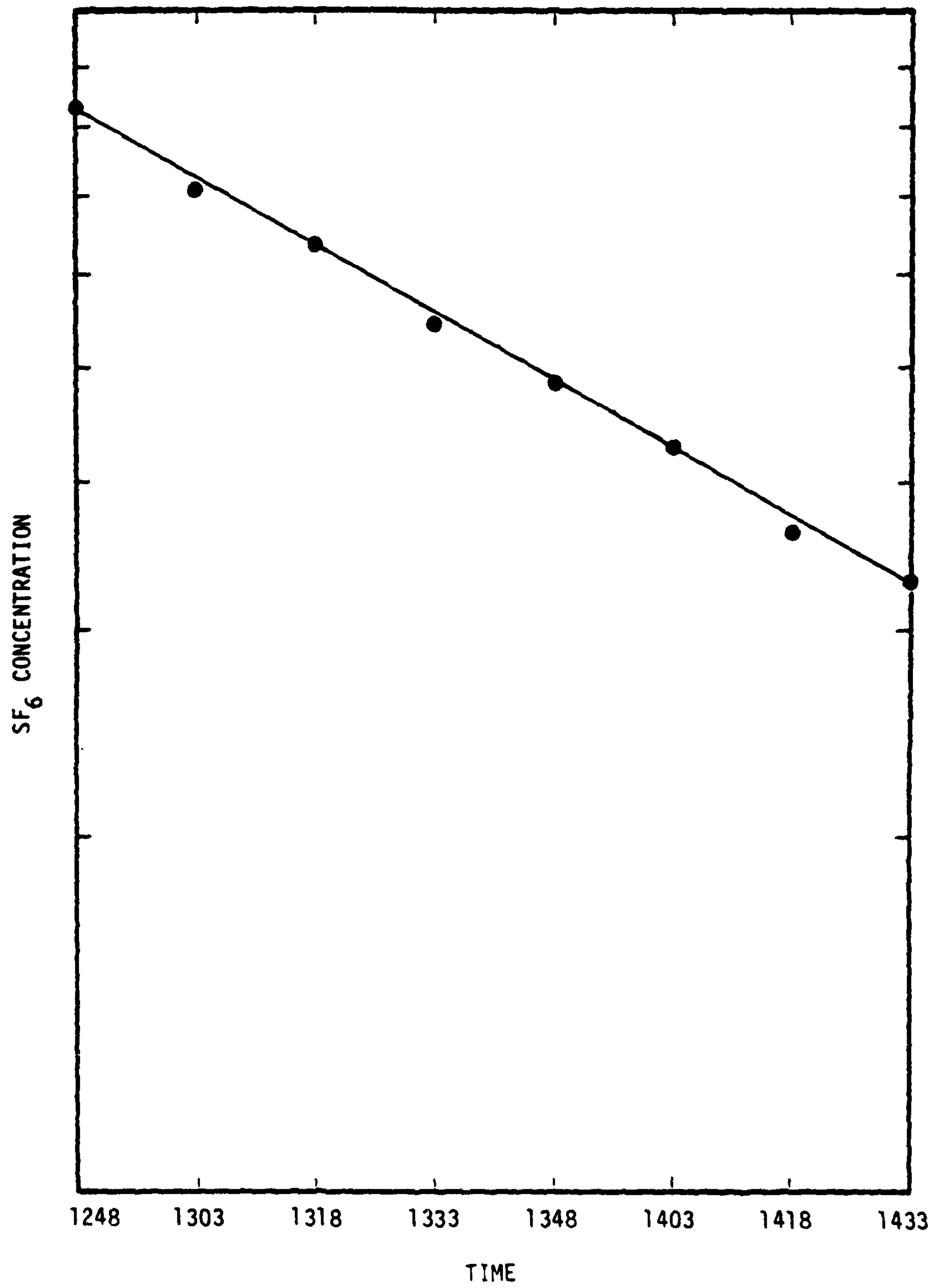

Figure B.5b Tracer Concentration Decay *versus* Time on 12/4/79 (P.M.) for Apartment No. 8121.

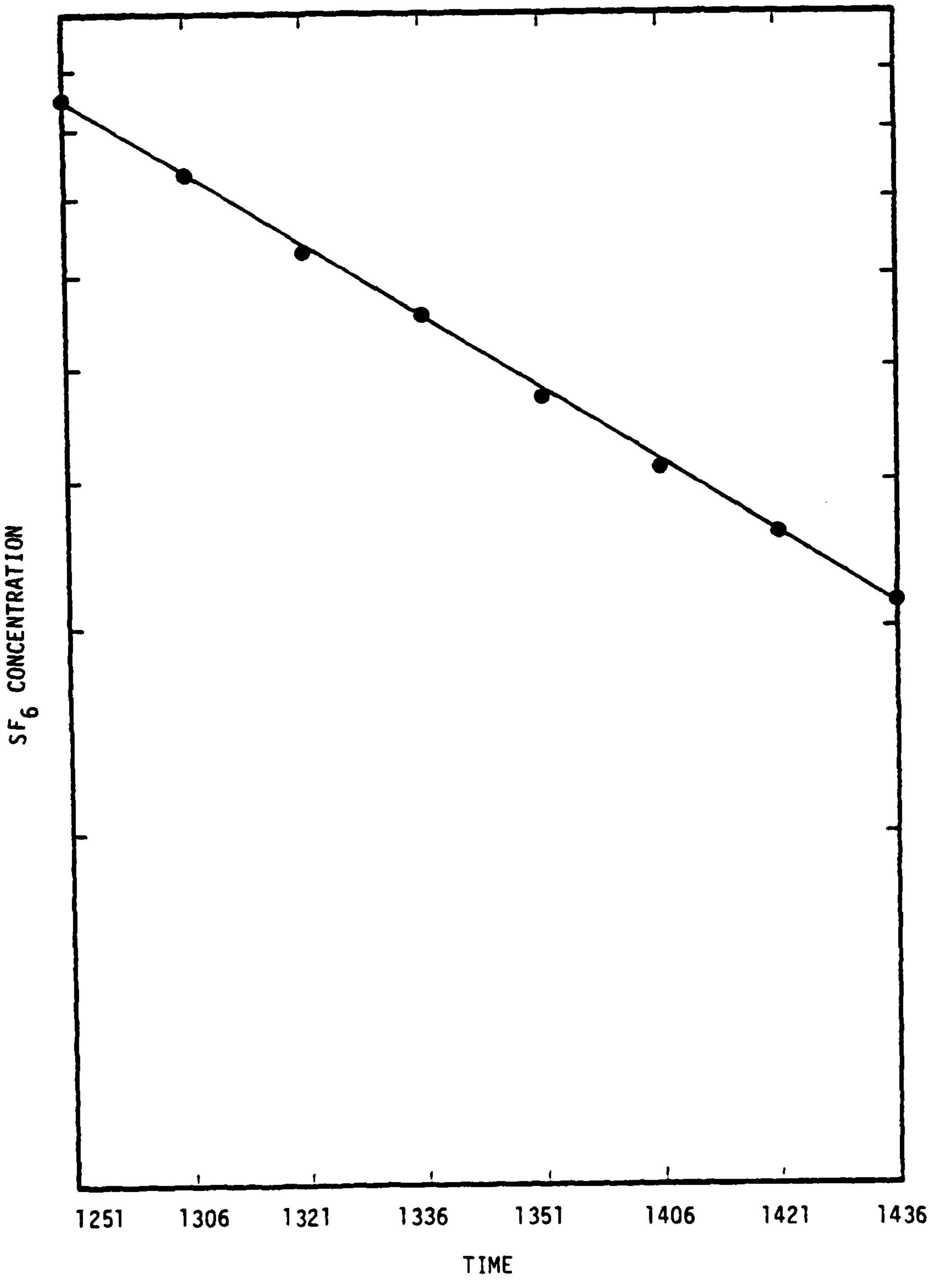

Figure B.6 Tracer Concentration Decay *versus* Time on 12/4/79 (P.M.) for Apartment No. 8133.

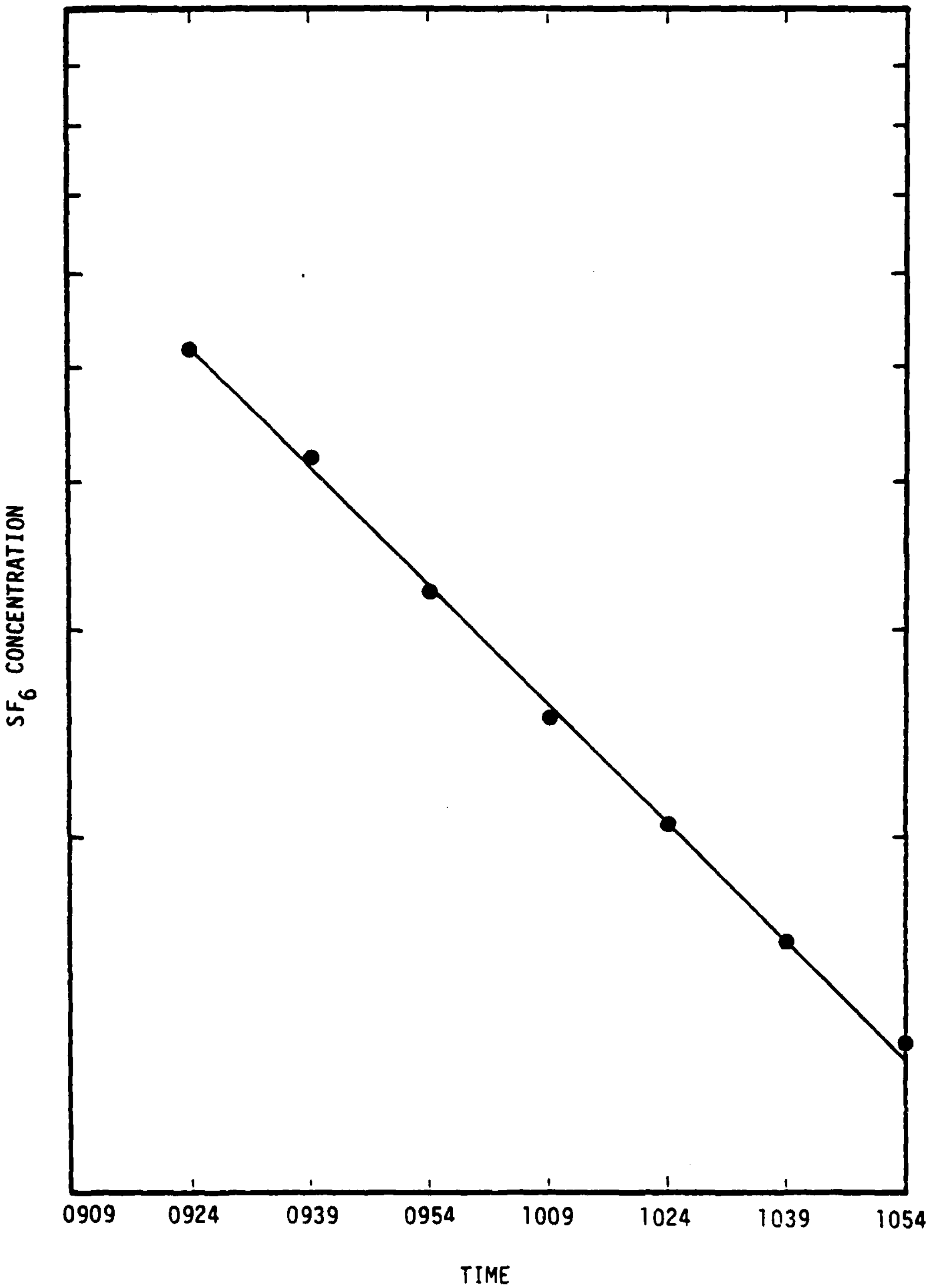

Figure B.7a Tracer Concentration Decay *versus* Time on 12/4/79 (A.M.) for Apartment No. 8151.

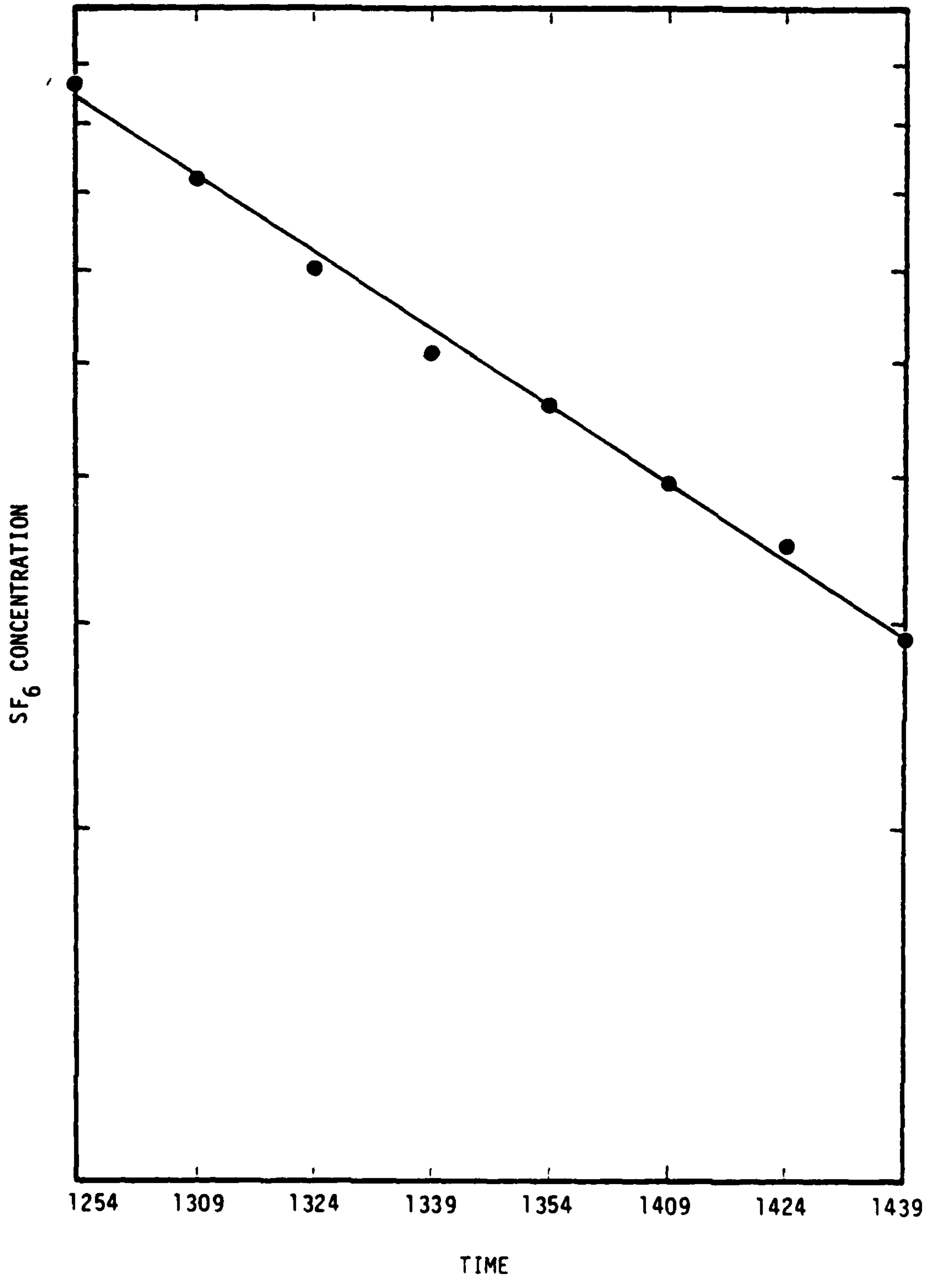

Figure B.7b Tracer Concentration Decay <u>versus</u> Time on 12/4/79 (P.M.) for Apartment No. 8151.

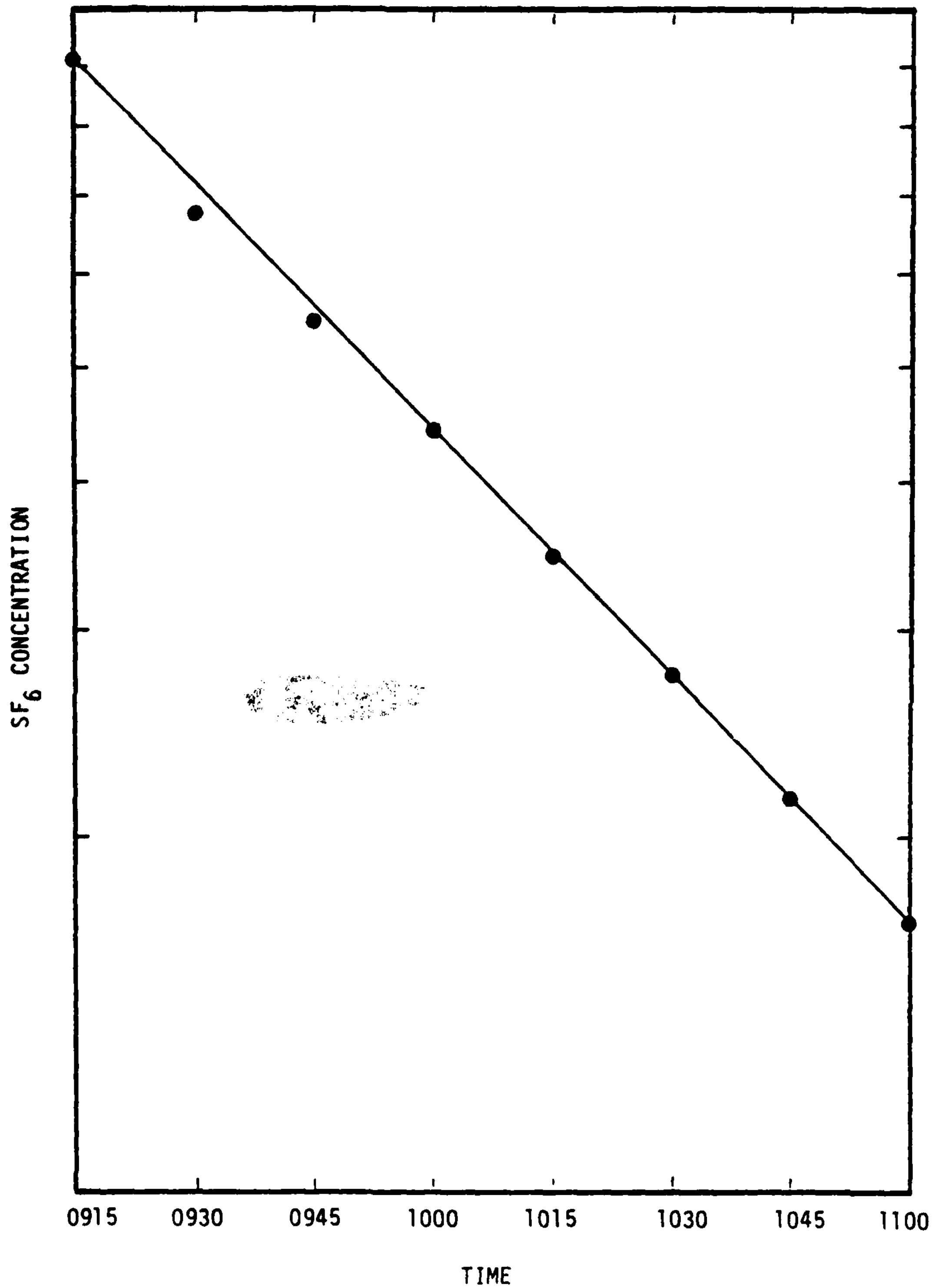

Figure B.8a Tracer Concentration Decay _versus_ Time on 12/4/79 (A.M.) for Apartment No. 8162.

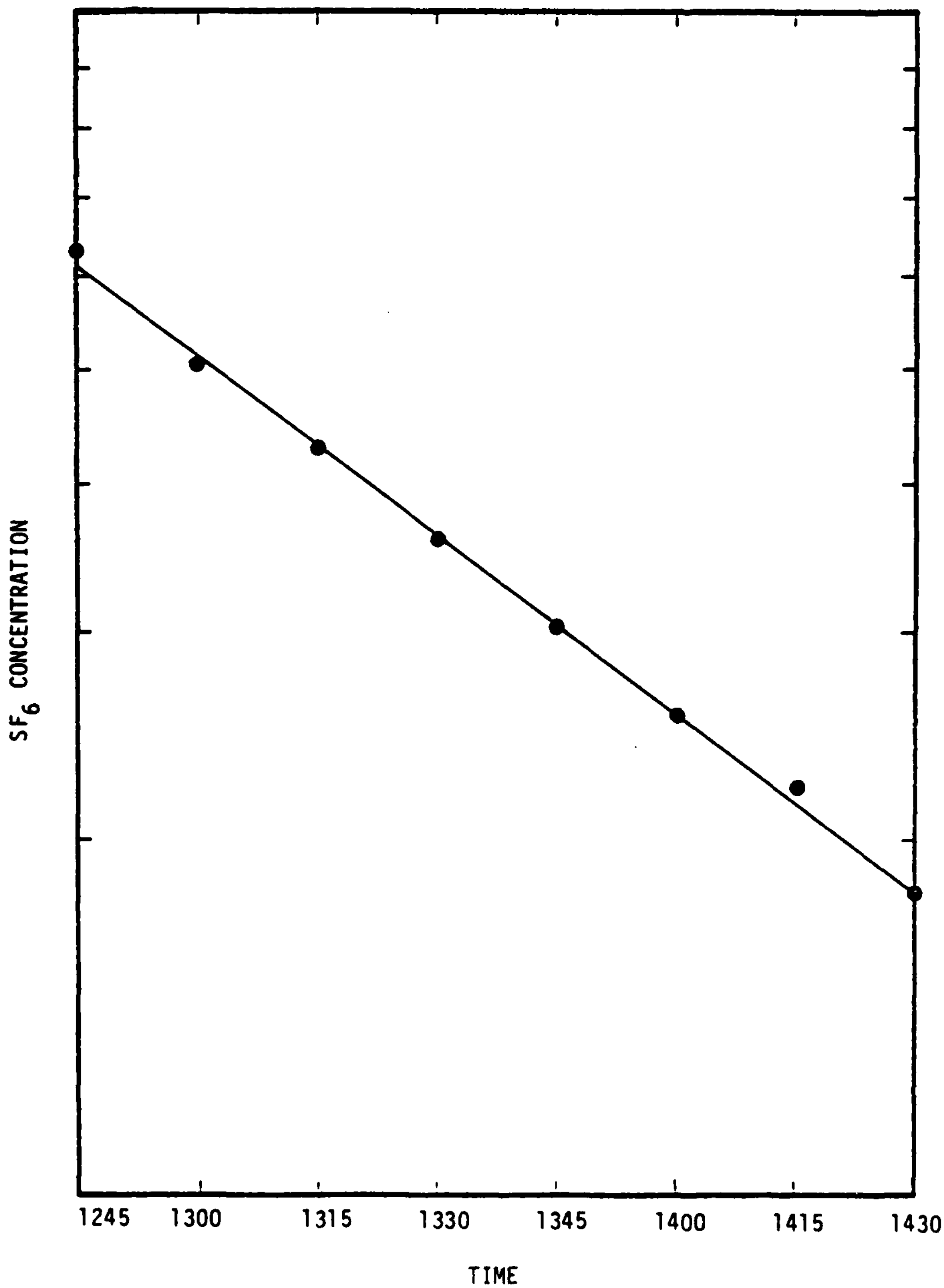

Figure B.8b Tracer Concentration Decay *versus* Time on 12/4/79 (P.M.) for Apartment No. 8162.

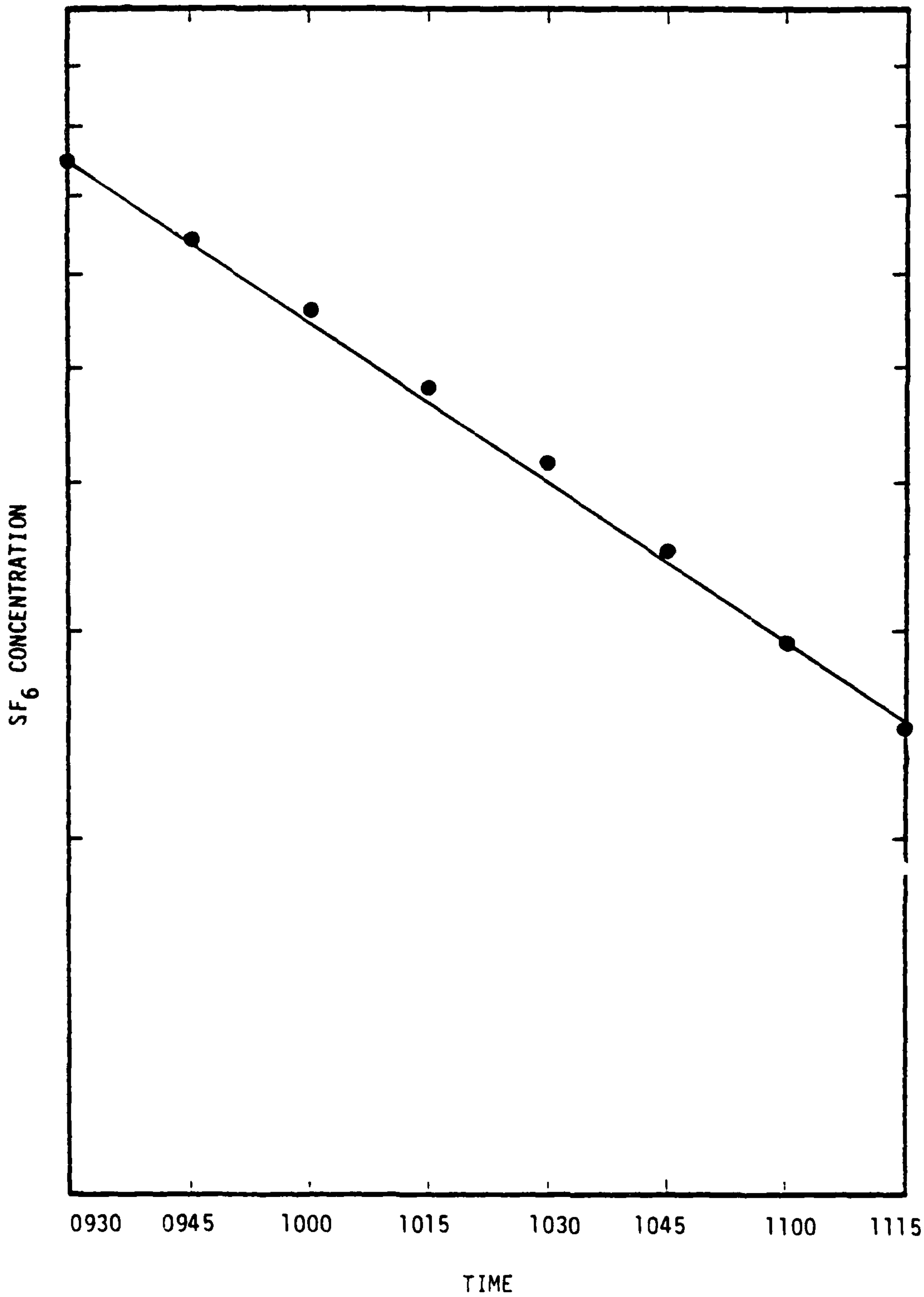

Figure B.9a Tracer Concentration Decay versus Time on 10/18/80 (A.M.) for Apartment No. 8705 (Vent System On).

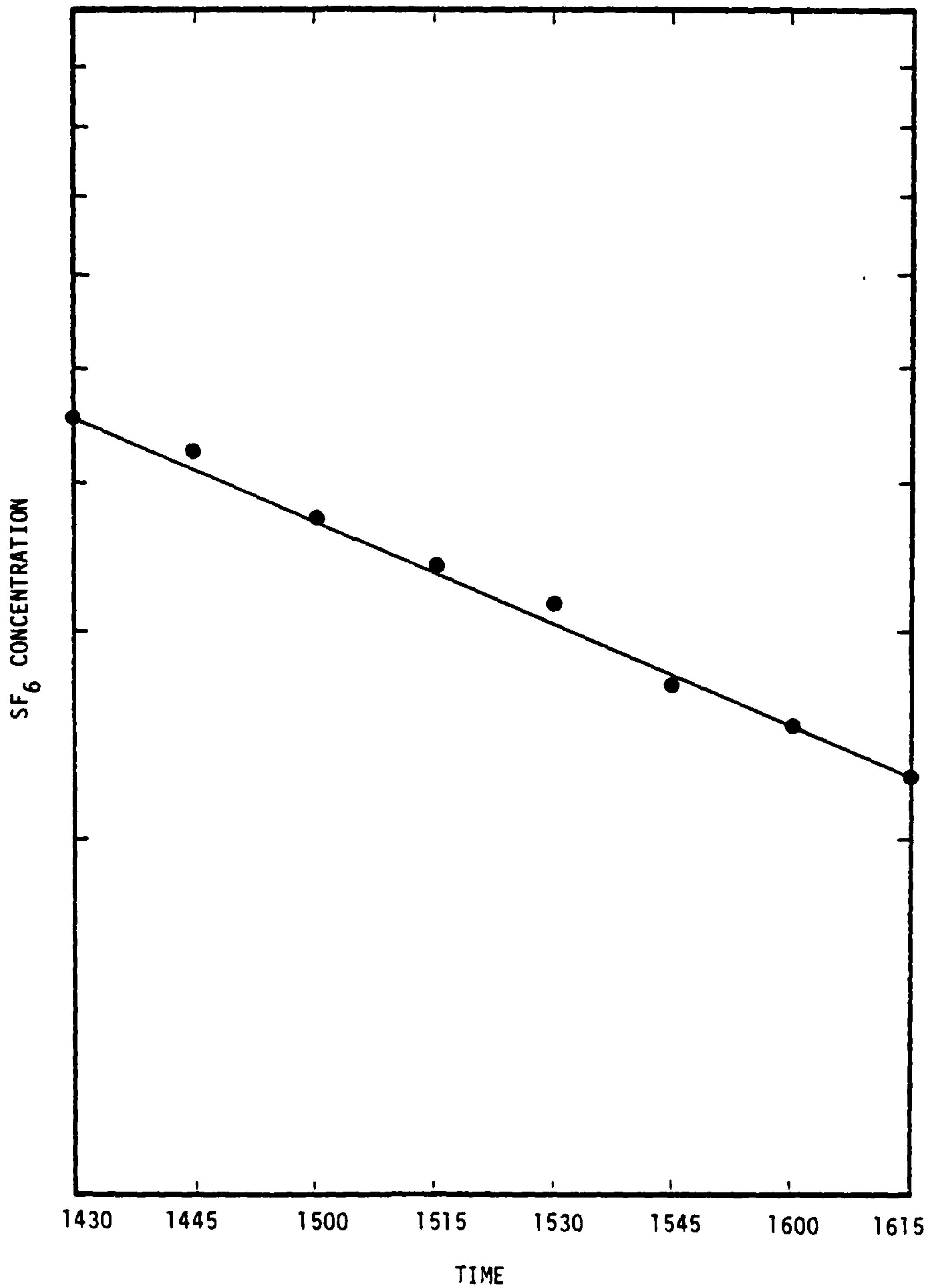

Figure B.9b Tracer Concentration Decay *versus* Time on 10/18/80 (P.M.) for Apartment No. 8705 (Vent System Off).

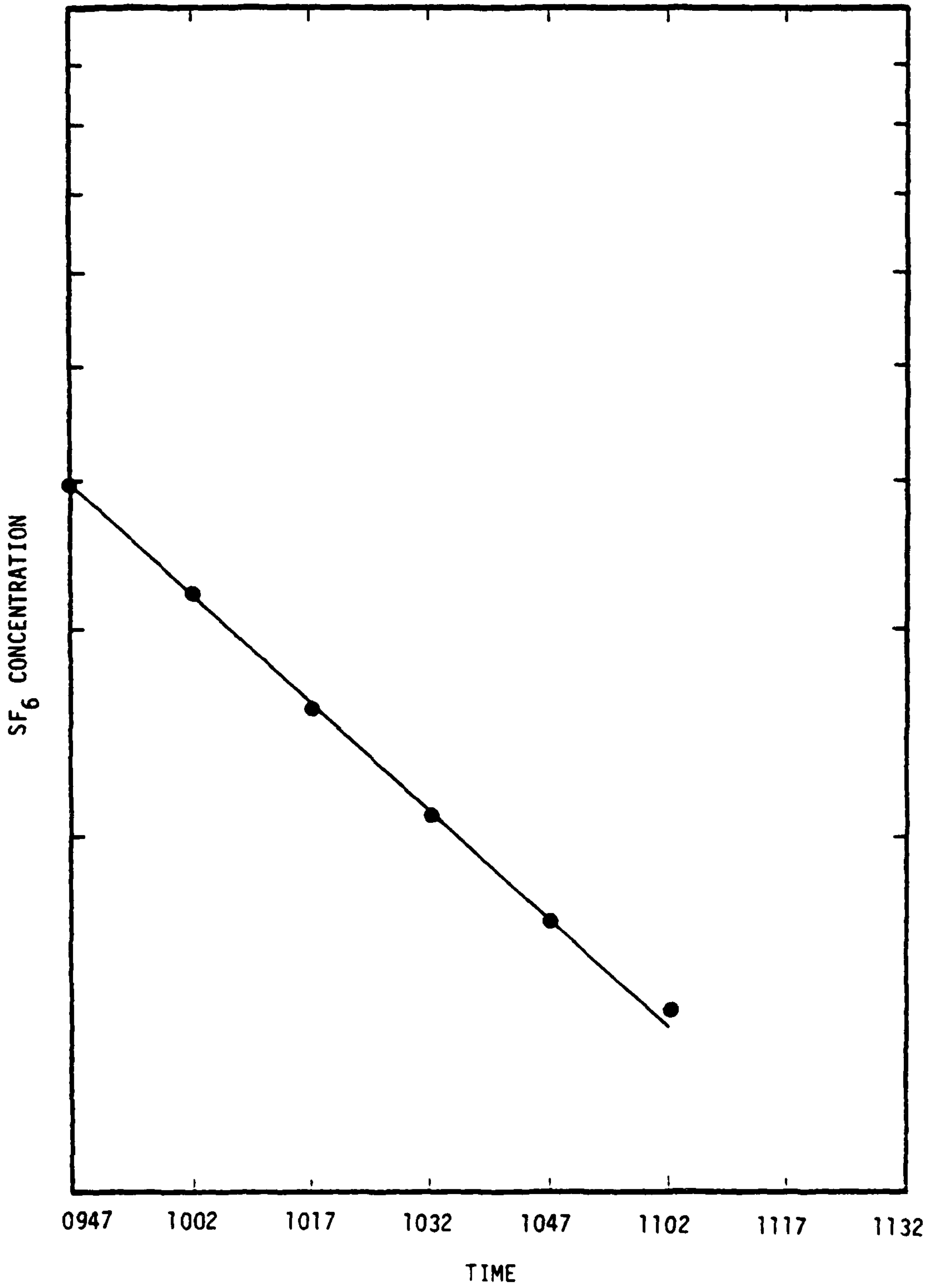

Figure B.10a Tracer Concentration Decay versus Time on 10/22/80 (A.M.) for Apartment No. 8134.

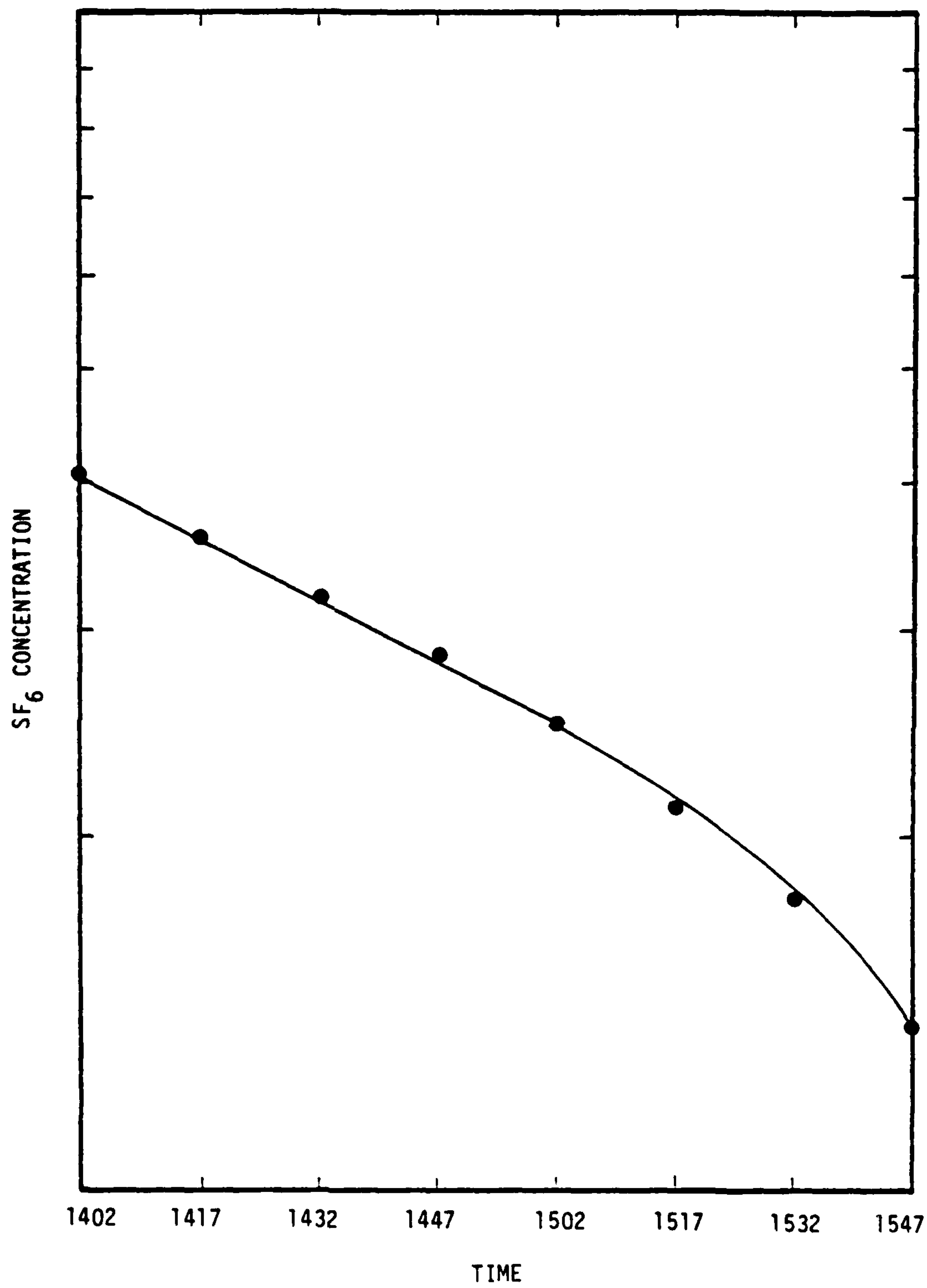

Figure B.10b Tracer Concentration Decay <u>versus</u> Time on 10/22/80 (P.M.) for Apartment No. 8134.

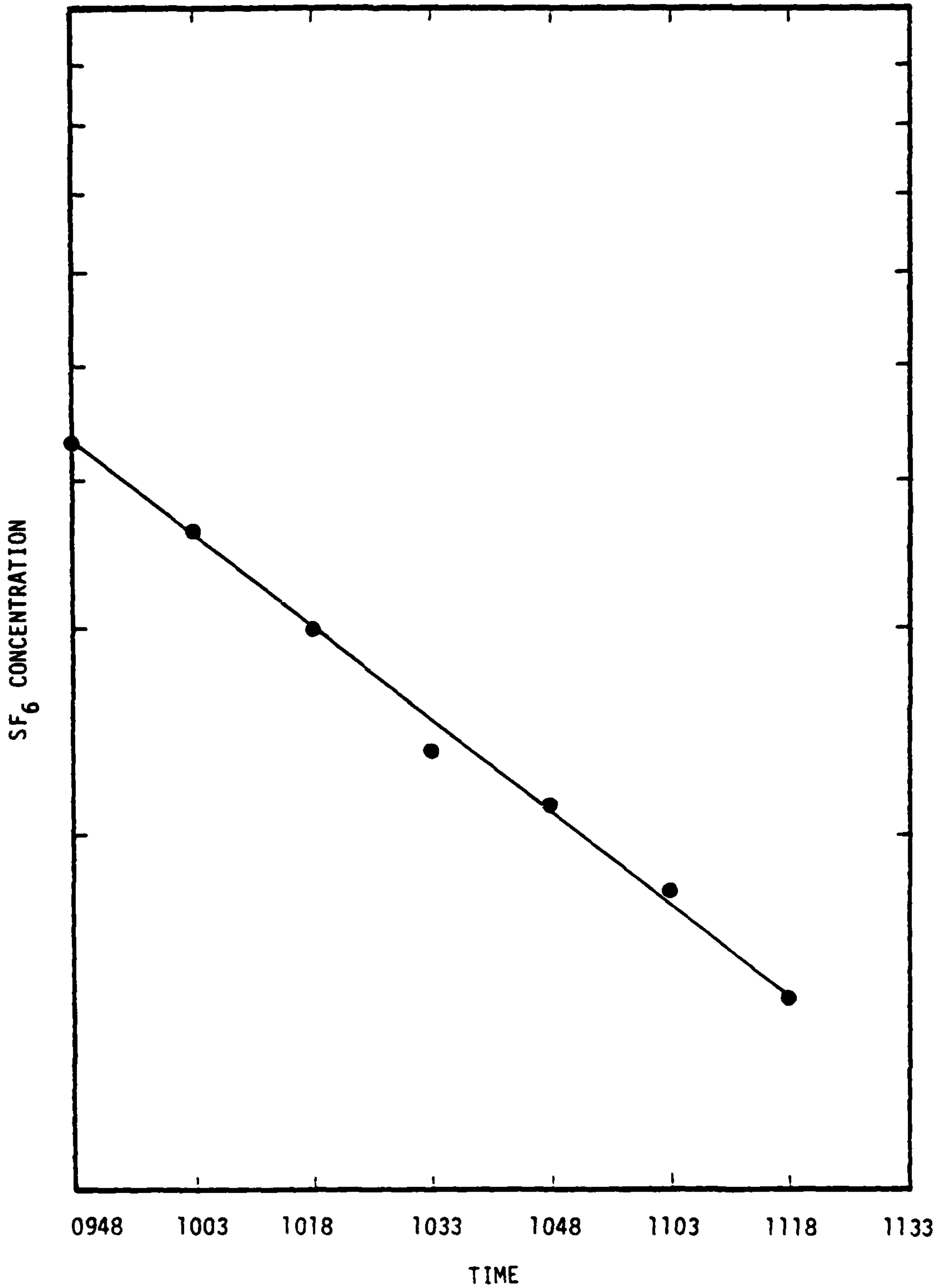

Figure B.11a Tracer Concentration Decay *versus* Time on 10/22/80 (A.M.) for Apartment No. 8135.

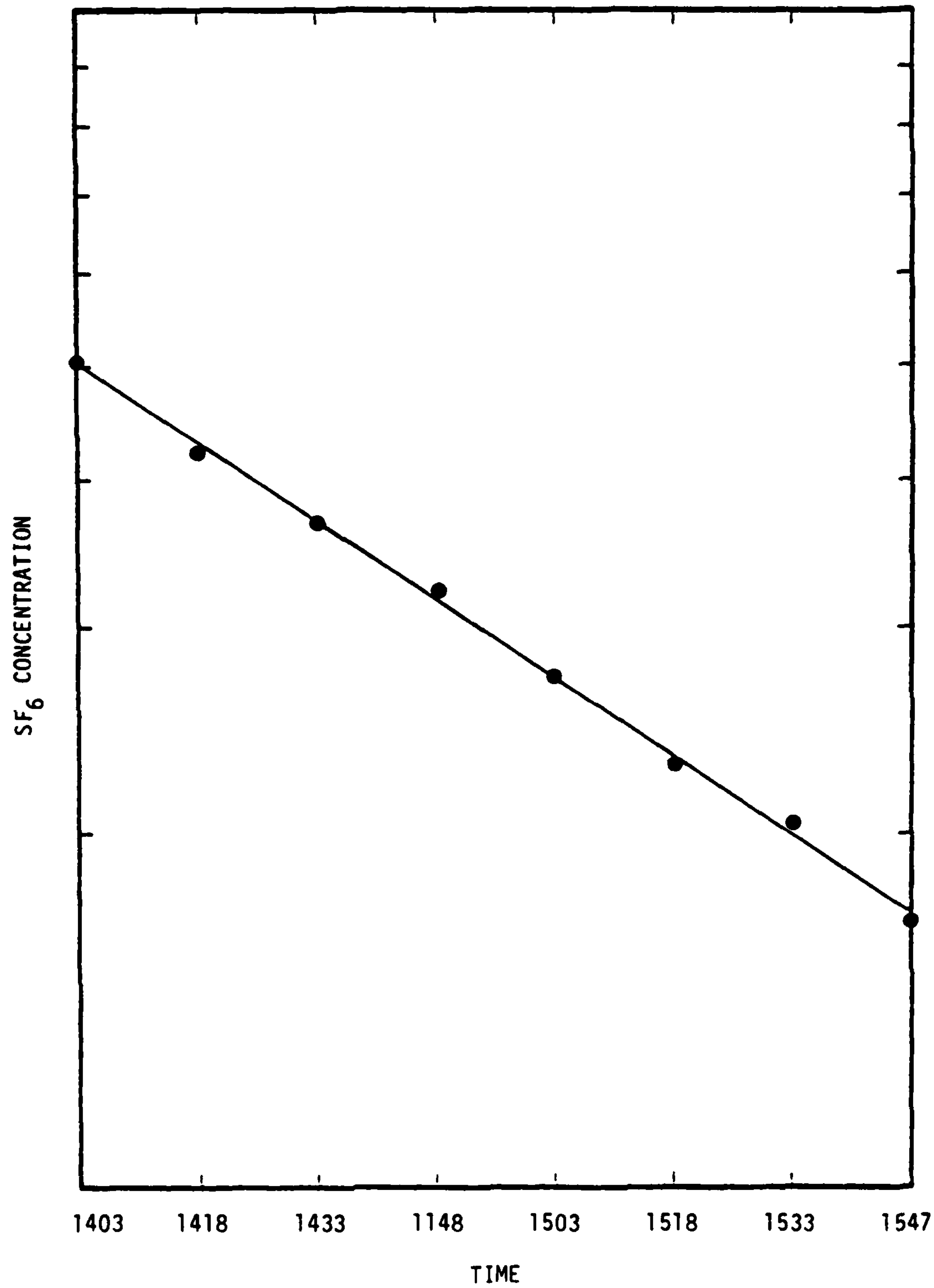

Figure B.11b Tracer Concentration Decay versus Time on 10/22/80 (P.M.) for Apartment No. 8135.

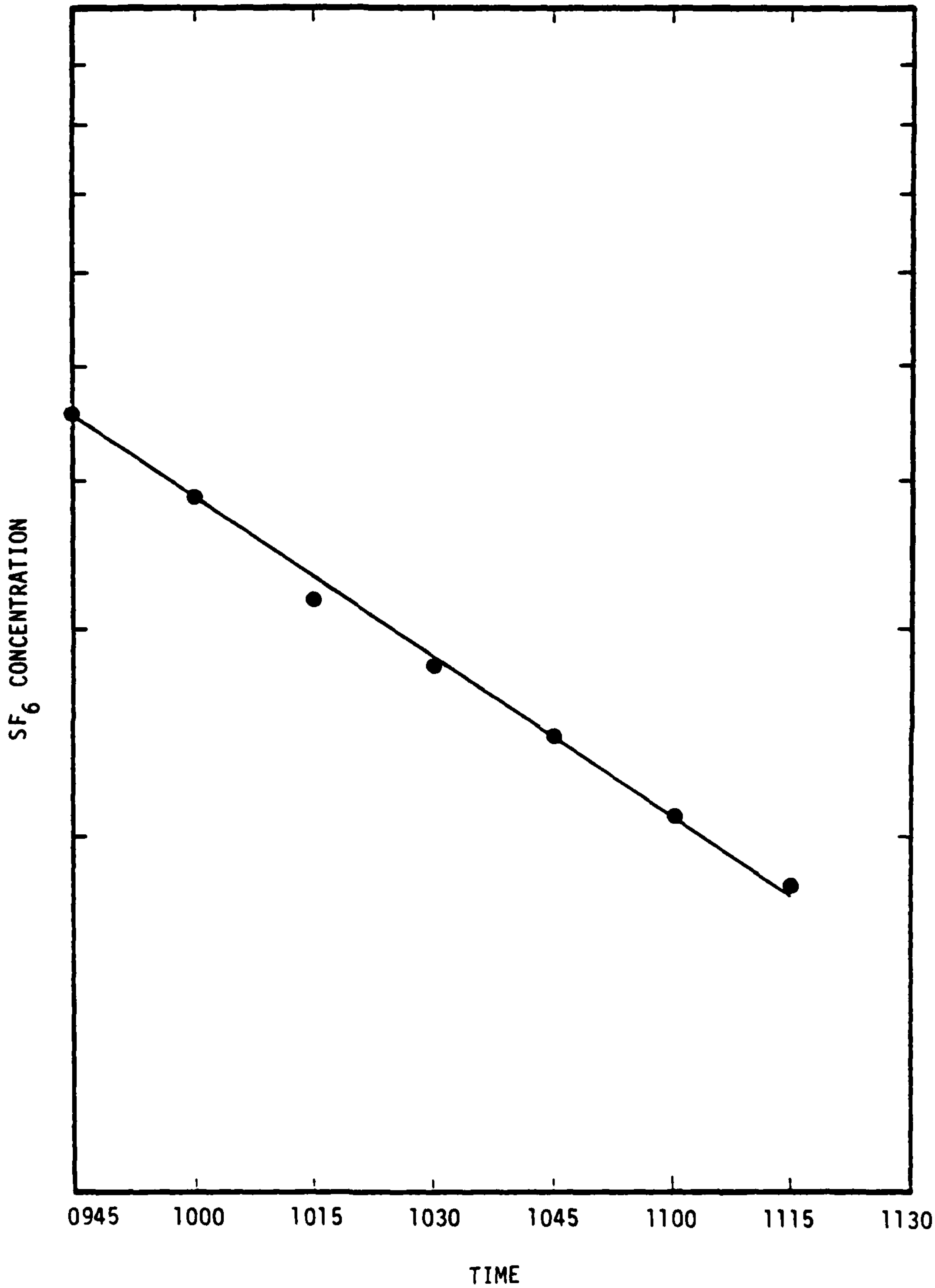

Figure B.12a Tracer Concentration Decay *versus* Time on 10/22/80 (A.M.) for Apartment No. 8152.

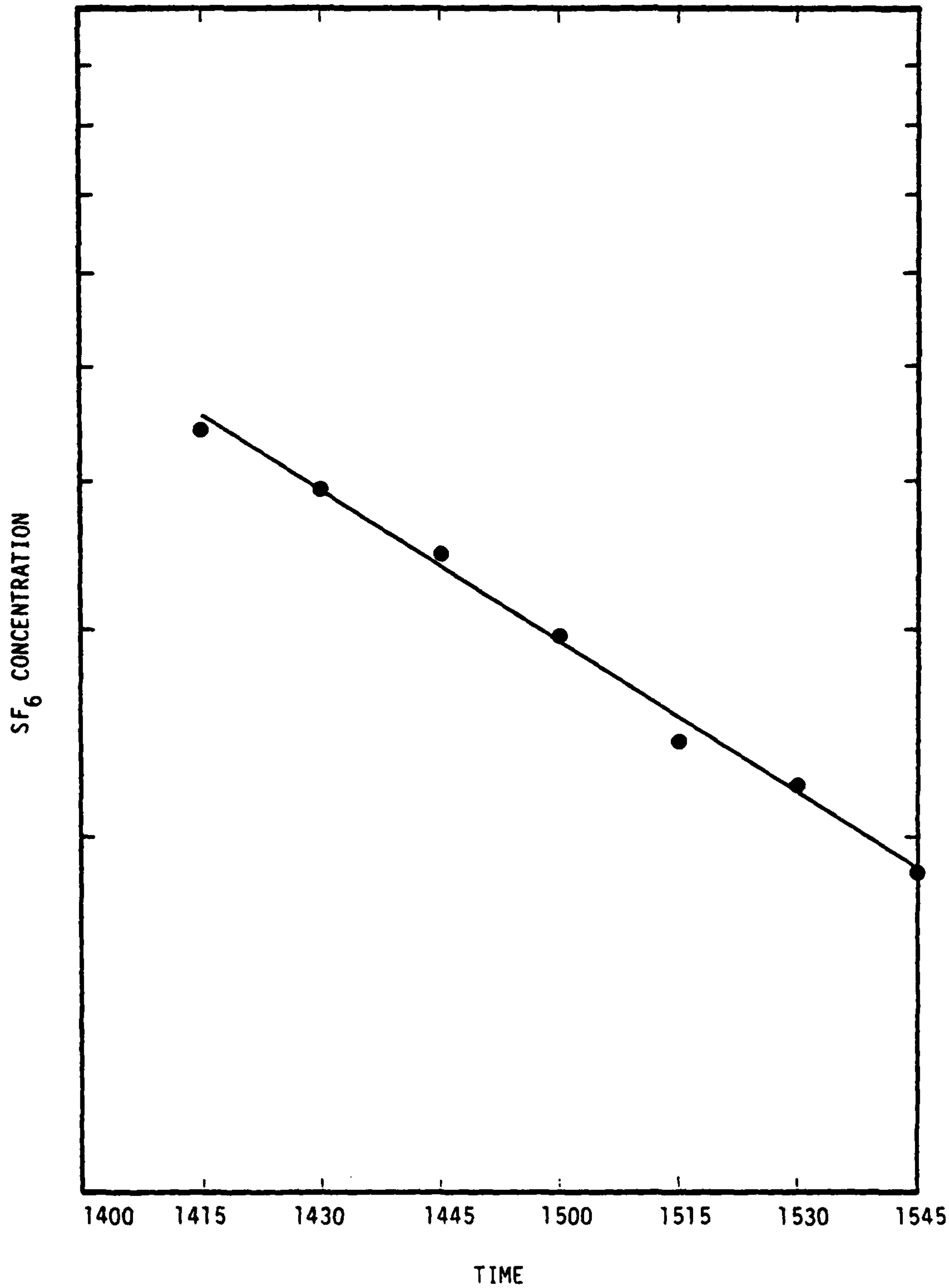

Figure B.12b Tracer Concentration Decay *versus* Time on 10/22/80 (P.M.) for Apartment No. 8152.

APPENDIX C

SIMULATION OF ENERGY CONSUMPTION
IN THE YEAR 1978
FOR APARTMENT NO. 8123 O'CONNOR CRESCENT
UTILIZING NBSLD AND S-CUBED
INFILTRATION DATA

In the following Appendix we graphically present tabular data for the energy consumption history of Apartment No. 8123 O'Connor Crescent for the year 1978. Actual energy consumption for heating and cooling were monitored for 1978, and serve as the basis for comparison with calculations.

The calculational model was NBSLD, used in two ways. In the first, NBSLD was used with the infiltration algorithm supplied with the code. The second calculation was performed in an identical manner, except that the S-Cubed infiltration regression equation determined in Reference [10] was used in place of the NBSLD algorithm. As is apparent, a significant improvement was obtained in the prediction of energy consumption by incorporating this more representative infiltration model.

LIST OF FIGURES AND TABLES - APPENDIX C

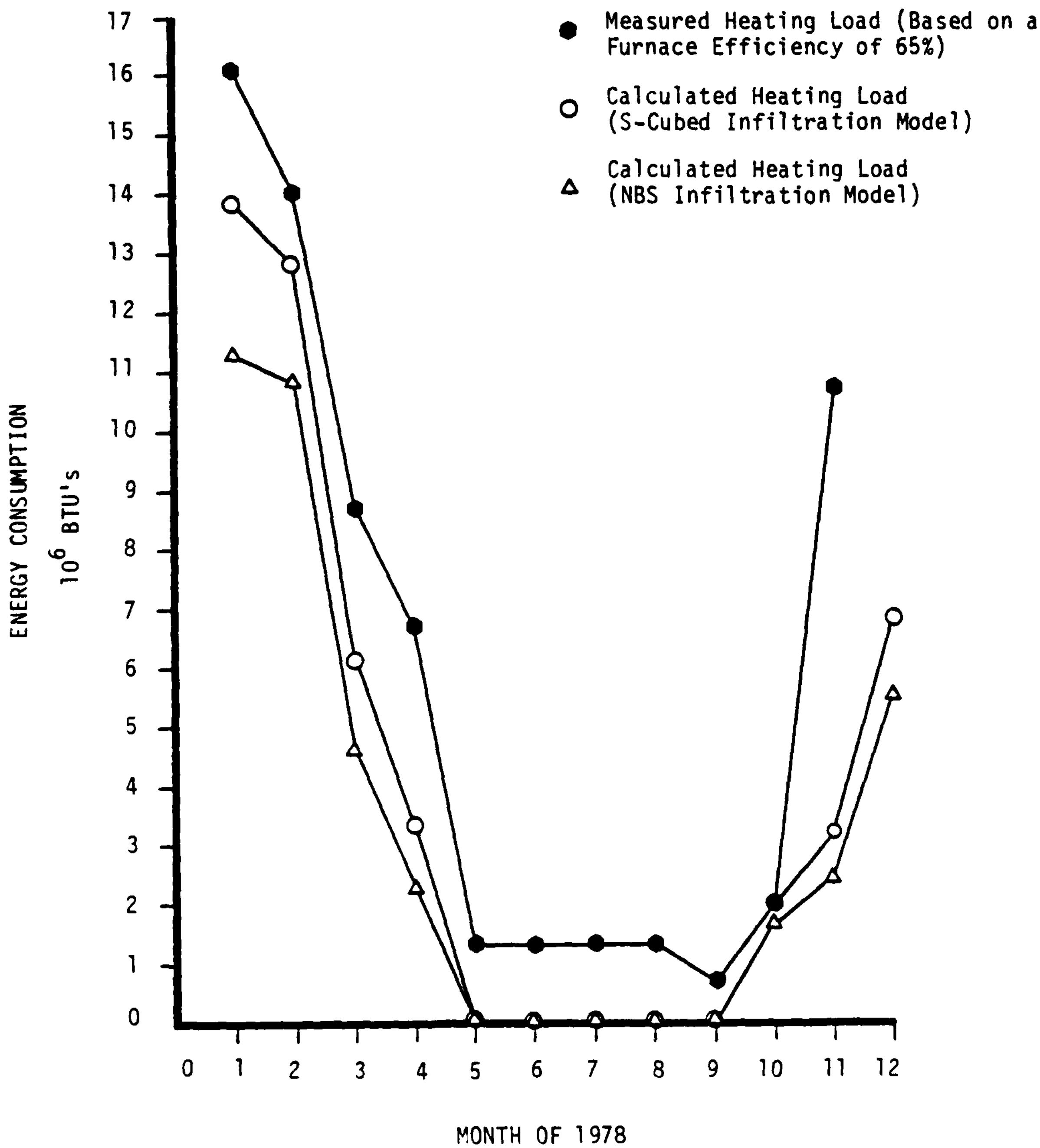

Figure C.1 Energy Consumption for Heating Apartment No. 8123 During 1978.

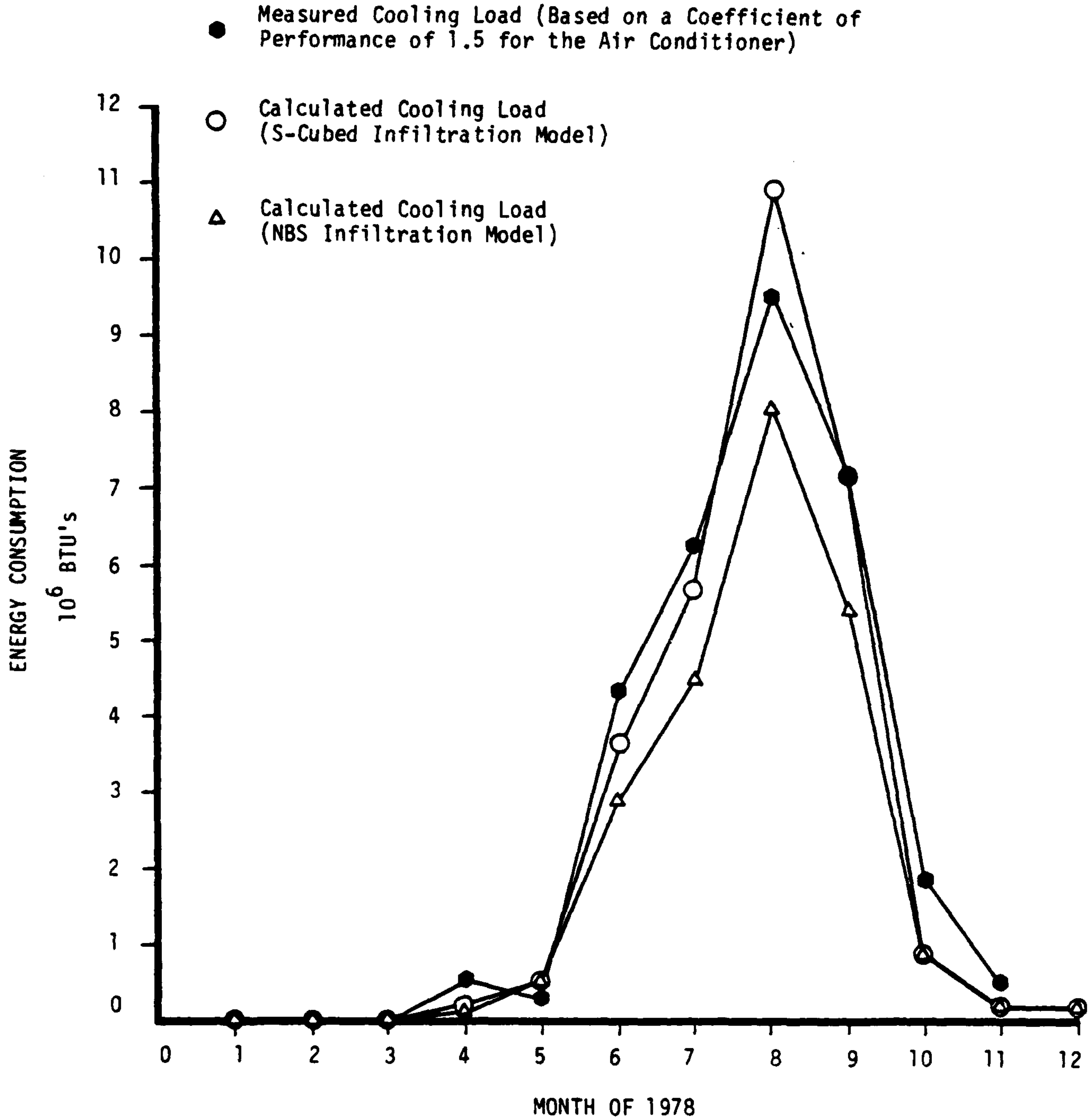

Figure C.2 Energy Consumption for Cooling Apartment No. 8123 During 1978.

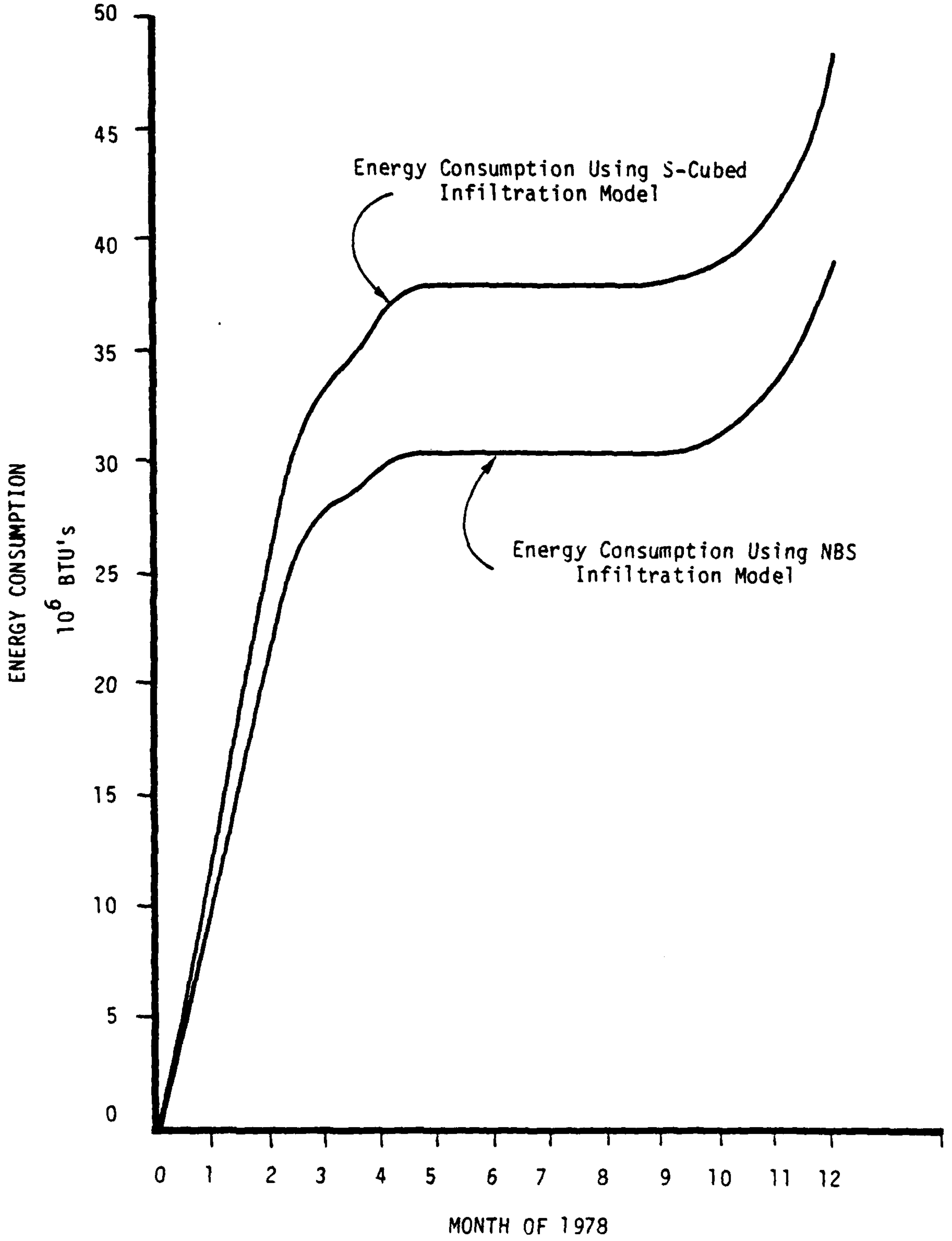

Figure C.3 Energy Consumption for Heating Apartment No. 8123 During 1978 -- As Calculated Using the NBSLD Computer Code.

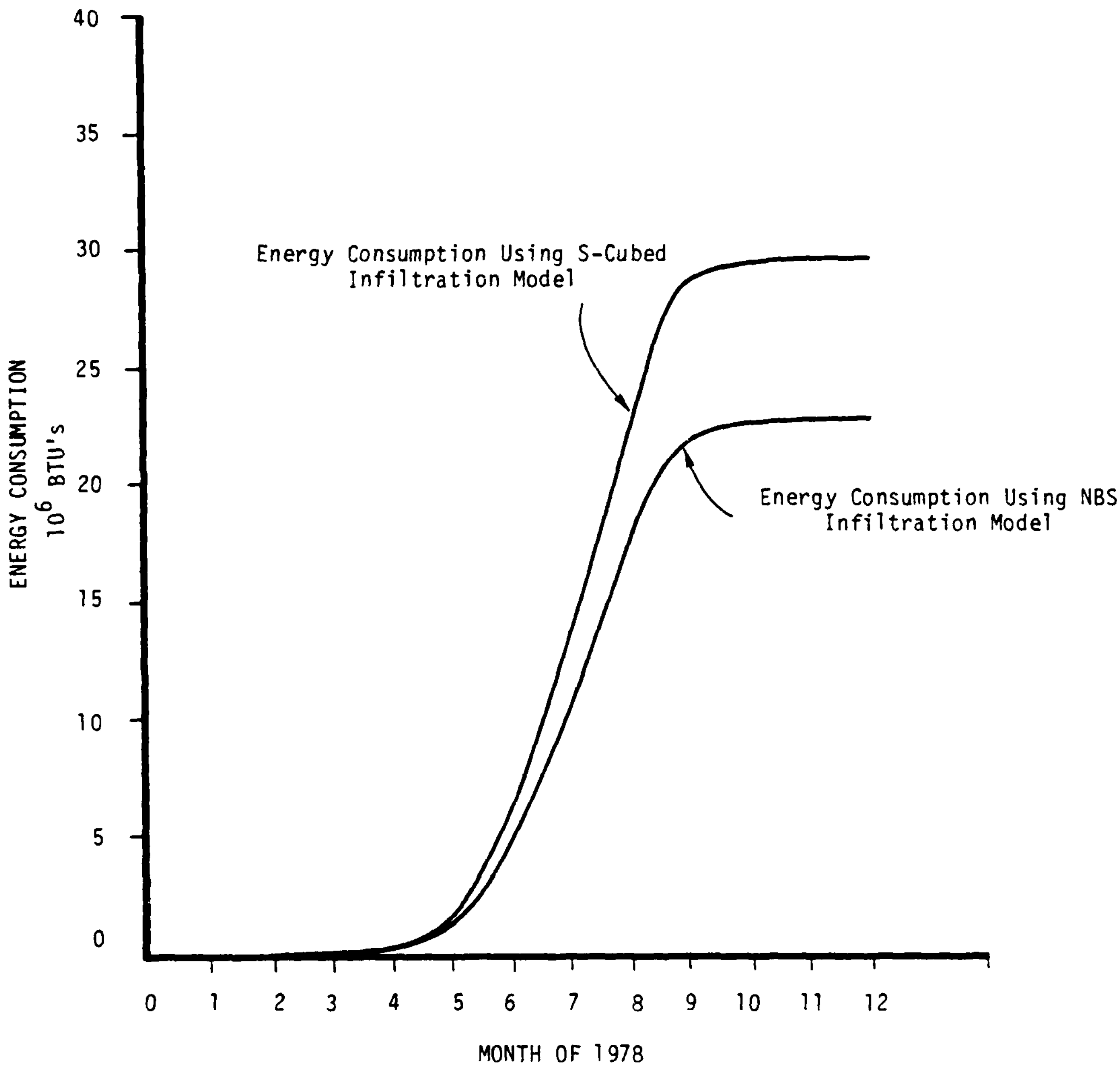

Figure C.4 Energy Consumption for Cooling Apartment No. 8123 During 1978 -- As Calculated Using the NBSLD Computer Code.

TABLE C-I

ENERGY USAGE FOR HEATING APARTMENT NO. 8123 DURING 1978

Month	Period	Measured Heating Load 10^6 BTU's			Calculated Heating Load 10^6 BTU's	
		Meter Reading		Corrected For 65% Furnace Eff.-10^6 BTU's	S-Cubed Inf. Model	NBS Inf. Model
		1000 Ft.^{3}	10^6 BTU's			
1	1/05 - 2/06	24	24.74	16.08	13.83	11.35
2	2/06 - 3/06	21	21.65	14.07	12.82	10.84
3	3/06 - 4/06	13	13.40	8.71	6.10	4.65
4	4/06 - 5/08	10	10.31	6.70	3.35	2.29
5	5/08 - 6/06	2	2.06	1.34	0.17	0.11
6	6/06 - 7/07	2	2.06	1.34	0.014	0.11
7	7/07 - 8/07	2	2.06	1.34	-0-	-0-
8	8/07 - 9/11	2	2.06	1.34	-0-	-0-
9	9/11 - 10/06	1	1.03	0.67	0.049	0.04
10	10/06 - 11/06	3	3.09	2.01	2.01	1.63
11	11/06 - 12/06	16	16.49	10.72	3.2	2.42
12	12/06 - 12/30	-	-	-	6.81	5.55

NOTE: Calculated heating loads for each time period are based on the number of days between meter readings -- inclusive of the initial meter reading, and exclusive of the final reading for each time period.

TABLE C-II

ENERGY USAGE FOR COOLING APARTMENT NO. 8123 DURING 1978

Month	Period	Measured Cooling Load 10^6 BTU's			Calculated Cooling Load 10^6 BTU's	
		Meter Reading		Corrected for an Air Cond. C.O.D. of 1.5 - 10^6 BTU's	S-Cubed Inf. Model	NBS Inf. Model
		KWHR	10^6 BTU's			
1	12/25 - 1/24	-0-	-0-	-0-	-0-	-0-
2	1/24 - 2/21	-0-	-0-	-0-	-0-	-0-
3	2/21 - 3/22	-0-	-0-	-0-	.01	.01
4	3/22 - 4/22	102	.35	.52	.19	.16
5	4/22 - 5/23	52	.18	.27	.57	.51
6	5/23 - 6/22	844	2.88	4.32	3.64	2.91
7	6/22 - 7/21	1214	4.14	6.21	5.65	4.46
8	7/21 - 8/23	1856	6.33	9.5	10.95	8.04
9	8/23 - 9/22	1395	4.76	7.14	7.08	5.42
10	9/22 - 10/20	354	1.21	1.81	.96	.85
11	10/20 - 11/22	109	.37	.56	.13	.13
12	11/22 - 12/30	-	-	-	.14	.10

NOTE: Calculated cooling loads for each time period are based on the number of days between meter readings -- inclusive of the initial meter reading, and exclusive of the final reading for each time period.

TABLE C-III

ENERGY CONSUMPTION IN APARTMENT NO. 8123 DURING 1978

Day	S-Cubed Infiltration Model		NBS Infiltration Model	
	Heating 10^6 BTU's	Cooling 10^6 BTU's	Heating 10^6 BTU's	Cooling 10^6 BTU's
15	5.86	-0-	4.83	-0-
30	12.02	-0-	9.83	-0-
45	19.88	-0-	16.37	-0-
60	26.10	-0-	21.76	-0-
75	31.36	-0-	25.98	-0-
90	33.81	.01	27.79	.01
105	34.76	.19	28.48	.16
120	37.0	.20	29.94	.17
135	37.63	.44	30.41	.36
150	37.70	1.31	30.46	1.12
165	37.71	3.35	30.46	2.70
180	37.72	6.12	30.46	4.97
195	37.72	8.85	30.47	7.13
210	37.72	13.02	30.47	10.19
225	37.72	18.19	30.47	13.90
240	37.72	22.66	30.47	17.32
255	37.72	26.48	30.47	20.21
270	37.72	28.55	30.47	21.87
285	38.15	28.96	30.86	22.26
300	39.15	29.15	31.64	22.44
315	40.11	29.16	32.42	22.46
330	41.69	29.19	33.54	22.48
345	44.11	29.32	35.51	22.59
360	48.39	29.32	38.99	22.59